Mapping Scotland's Hydropower Resource

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Abstract

Increased renewable electricity generation is key to the reduction of carbon emissions and has the added benefit of reducing reliance on imported gas and coal while increasing diversity of the generation mix. To encourage development of renewable generation the Scottish Government has adopted an ambitious 100% renewable electricity generation target to be met by 2020. Although hydropower has generally been considered insignificant in a UK context, when forming part of a Scottish target the resource becomes much more significant as the majority of the UK's existing capacity and potential for new capacity is located within Scotland.

Scotland has a long history of hydropower development with the majority of current operational capacity installed during the mid 20th century. Recent studies have produced a range of estimates for the remaining resource from 286 to 1000 MW. The studies undertaken have tended to rely upon catchment analogue methods or the use of regression equations to produce estimates of flow at sites of interest, with simple assumptions of installation costs and energy yield. This work uses a novel method combining time series flow data produced from a distributed hydrological model with GIS techniques and a detailed parametric cost model to enable a state-of-the-art hydropower resource model to be developed.

The use of time series flow data allowed investigation of the spatial and temporal characteristics of the resource to be made, both run-of-river and impoundment schemes to be investigated and a preliminary assessment of the impact of climate change to be performed. Three financial scenarios have been considered using 5%, 10% and 15% discount rates as this is the most sensitive variable when assessing the feasibility of hydropower projects, reflecting the cost of finance available and investors' attitude to risk. The spread of discount rates will account for changes in available subsidies, electricity prices and ongoing costs. Clearly availability of low cost finance and a low risk subsidy environment will have the largest impact on hydropower development. A major limiting factor was found to be the cost of grid connection; if this were reduced the potential figure could be higher.

The results of this work show that at a 10% discount rate, 440 MW of new run-of river hydropower potential capable of producing 1.7 TWh per year is available. Exploitation of this would represent an additional 4% contribution towards the Scottish Government's 100% renewable electricity target.

Declaration of originality

I hereby declare that the research recorded in this thesis and the thesis itself was composed and originated entirely by myself in the School of Engineering at The University of Edinburgh.

Niall Duncan

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Acronyms and abbreviations

2D	Two dimensional
3D	Three dimensional
AET	Actual Evapotranspiration
ASCII	American Standard Code for Information Interchange
BADC	British Atmospheric Data Centre
BFI	Base Flow Index
CCS	Carbon Capture and Storage
CEH	Centre for Ecology and Hydrology
CEGB	Central Electricity Generatin Board
DECC	Department for Energy and Climate Change
DEM	Digital Elevation Model
ET	Evapotranspiration
FAO	Food and Agriculture Organization of the United Nations
FDC	Flow Duration Curve
FIT	Feed in Tarrif
G2G	Grid to Grid Hydrological Model
GCM	Global Circulation Model
GCV	Generalised Cross Validation
GDAL	Geographical Dataset Abstraction Library
GIS	Geographical Information System
IEA	International Energy Agency
IDW	Inverse Distance Weighted
IFSAR	Interferometric synthetic aperture radar
IPCC	Intergovernmental Panel on Climate Change
KML	Keyhole Markup Language
LAI	Leaf Area Index
MORECS	The UK Meteorological Office Rainfall and Evaporation Calculation System
NPV	Net Present Value

NSHEB	North of Scotland Hydro Electric Board
OS	Ordnance Survey
PET	Potential Evapotranspiration
POC	Point of Connection
RCM	Regional Circulation Model
RMSE	Root Mean Square Error
RSS	Residual Sum of Squares
RO	Renewables Obligation
ROR	Run-of-River
SAAR	Standard Average Annual Rainfall
SEPA	Scottish Environmental Protection Agency
SHE	Systeme Hydrolgique European
SHEPD	Scottish Hydro Electric Power Distribution
SNH	Scottish Natural Heritage
SSE	Scottish and Southern Energy
SSH	Small Scale Hydro
TPS	Thin Plate Spline
TIFF	Tagged Image File Format
UKCP09	UK Climate Projections 2009
UKCP02	UK Climate Projections 2002
UKMO	UK Meterological Office
WG	Weather Generator

Nomenclature

Symbol	Description
CO_2	Carbon Dioxide
$^\circ$ C	Degrees Centigrade
ET	Evapotranspiration (mm)
ET_o	Grass reference evapotranspiration (mm)
P	Electrical power (W)
g	Gravitational constant (9.81 ms^{-2})
H	Hydraulic head (m)
H_{net}	Net hydraulic head (m)
H_{gross}	Gross hydraulic head (m)
Q	Flowrate, catchment discharge, stream flow (m^{3}s^{-1})
Q_{90}	90th percentile flowrate (m^{3}s^{-1})
Q_{95}	95th percentile flowrate (m^{3}s^{-1})
η_t	Turbine efficiency
η_e	Electrical efficiency
λ	Thin plate spline smoothing parameter
R^2	Coefficent of determination, Nash Sutcliffe model efficiency coefficient
R_n	Net radiation (MJ m^{-2} day^{-1})
G	Soil heat flux (MJ m^{-2} day^{-1})
$(e_s - e_a)$	Vapour pressure deficit of the air (kPa)
ρ_a	Mean air density at constant pressure (kg m^{-3})
c_p	Specific heat of the air (MJ kg^{-1} $^\circ$ C^{-1})
Δ	represents the slope of the saturation vapour pressure temperature relationship (kPa $^\circ$ C^{-1})
γ	Psychometric constant (kPa $^\circ$ C^{-1})
r_s	Crop bulk surface resistance (s m$^-$1)
r_a	Crop aerodynamic resistance (s m$^-$1)
u_2	Wind speed at 2 m (m s$^-$1)
$\bar{H}_o$	Daily extraterrestrial radiation (kW)
$\bar{H}$	daily horizontal surface radiation (kW)

1 Introduction

"I shall make electricity so cheap that only the rich can afford to burn candles."

– Thomas Edison

The provision of cheap, low carbon and secure electricity supplies to maintain economic well-being and support further economic growth is one of mankind's greatest challenges. As one of the major sources of CO_2 emissions, developments within the electricity industry will play a critical role in the fight against global warming.

The scale of the challenge is immense. In 2011 the International Energy Agency (IEA) issued a stark warning stating that if growth in electricity generation continues to rely on deployment of fossil fuel plant, by 2015 90 % of the allowable emissions (to limit warming to 2 ° C) for the energy sector will be locked in until 2035, increasing to 100 % of allowable emissions by 2017 (IEA, 2011). This leaves just 5 years for governments to introduce policy measures to accelerate growth of non fossil fuel generation such as renewables and nuclear and develop the technology to enable alternatives such as carbon capture and storage (CCS) to be deployed.

To reduce CO_2 emissions from the electricity industry, the UK and Scottish governments have set ambitious targets to increase the growth of renewables. The Scottish target is especially ambitious, aiming to meet 100 % of Scottish electricity demand from renewables by 2020 (Scottish Government, 2012). Until 2009 (when it was overtaken by wind power) hydropower was the single largest source of truly renewable electricity in the UK, with the vast majority of installed capacity located in Scotland. Although small in UK terms roughly 10 % of electricity generated in Scotland is provided by hydro (Scottish Government, 2012).

Since the heydays of significant Scottish hydropower development in the mid 20th century several studies have been undertaken to quantify the remaining resource with a wide range of estimates produced. The aim of this work is to provide a robust estimate of Scotland's remaining resource to show what contribution it can make to the Scottish Government's 100 % renewable electricity target (Scottish Government, 2012). Previous studies with the notable exception of the Salford Study (Salford Civil Engineering Ltd, 1989) have only produced aggregate figures, this work will produce maps and mappable data as a key deliverable, allowing an up-to-date assessment of potential sites to enter the public domain. A changing climate will impact rainfall patterns and volume, and subsequently the available hydropower resource. This work will also investigate the potential impact a changing climate will have on the available resource.

Hydropower is a very site specific resource, relying upon local hydrology and geography to produce power. Unlike wind power where wind speed estimates made at the kilometre scale are suitable for resource assessment, hydropower must be assessed at a higher resolution to successfully identify localised co-occurrences of steep slopes and adequate river flows. In addition every hydropower installation is different with a unique design, set of costs and hence economic feasibility. This work provides a fully integrated hydropower costing model, allowing different site specific designs to be costed and trialled against the available resource to determine the optimum size of turbine and penstock. To fully investigate hydropower potential over a wide area such as a country, while trialling different scheme configurations, it is necessary to perform a very large number of unique local assessments. This is achieved through use of a database that can be queried for site flow and elevation data which can then be input to the resource model allowing assessment of a large number of design options.

The Intergovernmental Panel on Climate Change (IPCC) stated in its 4th report that climate warming experienced since the industrial revolution can be attributed to human activities with a very high confidence (IPCC, 2007). Prior to this there had been general consensus on possible harm that climate change could cause, leading to the Kyoto Protocol (United Nations, 1998) which introduced targets and market based mechanisms designed to reduce individual nations' emissions of green house gases. As a result of international policy the European Union introduced legally binding targets for the reduction of CO_2 for member states with the UK government committed to supply 15 % of energy demand from renewables by 2020 (DECC, 2011b). In 2011 the Scottish Government announced a revised target for renewable electricity generation requiring the equivalent of 100 % of Scotland's electricity demand to be met from renewable sources by 2020 (Scottish Government, 2012).

When viewed in a UK context hydropower is generally considered an insignificant source of energy providing just 1.7 % of the 384 TWh of electricity consumed in the UK during 2010 (DECC, 2011b). In a Scottish context it becomes more important with 1422 MW of installed capacity capable of supplying approximately 13 % of Scotland's gross electric demand (Scot-

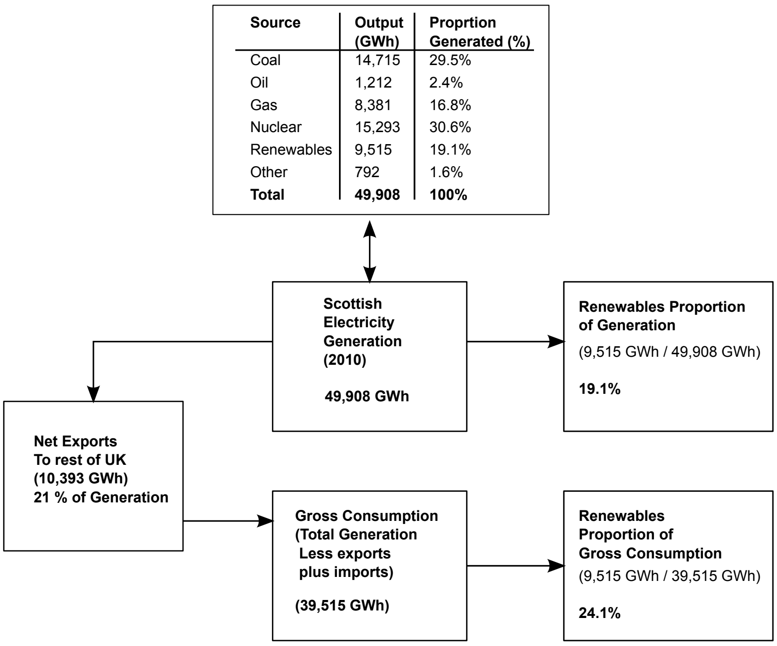

Figure 1.1: Calculation methodology for the Scottish Government's 100 % renewable target (Scottish Government, 2012)

tish Government, 2012). Scotland exports 25 % of its electricity production so to view hydropower in this way is a little unfair; when compared to total generation within Scotland hydropower produces some 10 % of total generated electricity. However the higher 13 % figure forms hydropower's contribution the 100 % target as per the Scottish Government's preferred methodology (see Figure 1.1). As such the role of existing hydropower towards meeting the 100 % renewable target is already significant and could increase greatly if additional capacity is deployed.

Several studies have concluded that rainfall in mid to high latitudes will increase due to warmer air temperatures especially during the winter with a greater number of intense precipitation events (Bergström et al., 2001; Intergovernmental Panel on Climate Change, 2007; Lehner et al., 2005). The amount of summer evapotranspiration is also expected to increase. In terms of impact upon hydropower it is likely that yields will increase in the winter while decreasing in the summer. Currently no assessment of the impact of climate change has been made on the Scottish hydropower resource. This work will use the best available climate change model data produced by the UKCP09 project to perform an assessment of the likely change to hydropower production under a future climate.

1.1 Research Objectives

This project will attempt to answer the following question:

> What contribution can hydropower make to Scotland's long term renewable energy ambitions?

It is proposed that development of geospatial processing techniques and a physically based hydrological model will allow a robust and physically complete estimate of the extent and characteristics of the technical Scottish hydropower potential to be computed. These tools will be coupled with a financial model of component and site development costs to allow the economic potential to be found.

This project will provide a robust survey of the temporal and spatial distribution of the remaining resource, supply a merit order of sites with investment potential, and provisionally consider how these might change under climate change.

The objectives of this work are summarised:

- Development of gridded time-series datasets for the period 1961-2005 providing a coherent measure of rainfall, evapotranspiration and temperature to enable use of a Scotland wide hydrological model.
- Creation of a hydrologically consistent representation of Scotland's river system for use with a distributed hydrological model, and an integrated hydropower search method.
- Development of a distributed hydrological model of Scotlands river systems, to enable production of datasets of historic river flows, at daily time resolution for the period 1961-2005.
- Development of a hydropower plant model which will allow assessment of energy yield for different scheme configurations given site specific flow and geographical characteristics. This model will allow scheme component costs to be calculated enabling a cost benefit analysis to be performed for trialled site designs and identification of the optimum design.
- Production of datasets of suitable locations for financially viable hydropower projects,

and likely scale and characteristics, for a range of scenarios with different underlying assumptions.

- Assessment of the likely impact of climate change upon hydropower production by modelling the performance of hydropower schemes under future climates.

1.2 Contribution to Knowledge

The need for this work arises from the disagreement between existing studies of the Scottish hydropower resource. It is also difficult to fully assess the credibility of existing work due to omission of key details from reports and a general lack of reported findings.

The existing Scottish studies rely upon simple extrapolation using catchment analogues or regression based methods to develop flow duration curves to estimate flows at sites. While these methods are capable of producing acceptable estimates of flow duration curve shape and magnitude at ungauged locations, no consideration is made of actual catchment hydrological response to rainfall and evapotranspiration. Using a distributed hydrological model to produce estimates of river flows within catchments provides a more physically complete method of performing a hydropower assessment and in theory should provide a better representation of the underlying hydrology of ungauged catchments. The ability to produce consistent long-term daily flow time-series is particularly useful as this allows the potential for impoundment based sites to be assessed in a complete way, as the operation of reservoirs can only be considered based upon the inflow and release rules for a reservoir of given size. Time series flows also allows the average daily generation of run-of-river sites to be calculated.

A novel method combining flow data produced using a distributed hydrological model with project yield and financial models is presented to make use of the best available meteorological and geospatial data for Scotland. This enables a search for economically 'optimal' run-of-river and impoundment based hydropower sites for a range of discount rate scenarios. This study improves on those previously undertaken by enabling a fully repeatable search methodology that can be parameterised to account for different costs and revenue streams and utilises a more physically complete method for estimating river flows.

The use of a hydrological model to produce estimates of flow is more challenging than other empirical techniques commonly used such as FDC analogues. This approach has been employed to take advantage of the relatively data rich context enjoyed by Scotland and to allow a more complete characterisation of the variability and potential change of the resource. It is hoped that demonstration of the techniques developed within this work for a Scottish assessment will encourage use in less data rich areas where hydropower resource is not as widely utilised. In particular, if long term gauged river flow time-series are unavailable for a region, this approach would allow the characterisation of flow necessary for hydropower resource assessment using meteorological data and a limited amount of river flow data for model calibration.

This is the first assessment of climate change impact on the Scottish hydropower resource. Given the role hydropower plays in the Scottish generation mix the findings presented here warrant further investigation into this area.

Several new datasets were created to allow this work to be completed. Gridded datasets of interpolated rainfall, evapotranspiration and daily mean temperature have been created. A fully addressed rivers dataset has been created and combined with available DEM data to enable an iterative search for suitable hydro locations to be made. These datasets could prove to be particularly useful for other engineering or water management applications.

An implementation of the G2G model enhanced with a snowmelt model has been created using efficient C++ code that is capable of operating at high resolution while still offering acceptable run-times.

Maps of locations of sites have been created at a national level, however results are best viewed at 1:50,000 scale. Details of identified sites including financial characteristics are provided as tables in Appendix B.

1.3 Thesis Outline

This thesis is made up of 8 chapters and 2 Appendices, the current chapter provides an introduction to the scope and objectives of this work.

Chapter 2 provides an introduction to hydropower, its development and use in Scotland. A discussion of the fundamentals of power production using water turbines, the types of scheme design and the role of economics on site design is undertaken. The existing studies of hydropower potential carried out in Scotland and elsewhere are discussed. The essential requirements of elevation and stream flow are discussed in terms of Scotland's topography and hydrology. An introduction to hydrological modelling and the modelling method applied is outlined.

Chapter 3 gives an overview of available interpolation methodologies suitable for creating gridded areal rainfall surfaces from point rain gauge data and the advantages of doing so. Details of the thin plate spline gridding procedure applied in this work and how the resulting datasets were validated are discussed. Details of use of how the FAO 56 Penman-Monteith method was used to create monthly gridded estimates of evapotranspiration using gridded data developed by the UK Met Office (UKMO) and how the resulting dataset was validated is discussed.

Chapter 4 discusses the development of raster and vector based rivers datasets using the Arc Hydro model to enable use of a distributed hydrological model and development of a hydropower search methodology. A discussion of the required resolution and accuracy of the resulting data is made.

Chapter 5 explains how a revised implementation of the G2G distributed hydrological model was developed, calibrated and validated to produce daily long-term time series of flows across Scotland's river network. A discussion of the required computational resource and available options is made. The development framework in terms of coding language, flexibility and performance is provided.

Chapter 6 discusses the development of a hydropower search routine to interrogate the available head and flow data saved at points along the vector river dataset. The financial costing model is introduced and its development discussed. The impact of component sizing on scheme economics is provided based upon findings from simulated hydropower schemes. An example of output from the hydro search model is provided including the ability to produce daily time-series power production. A method for assessing the available storage that can be provided by dams of varying size at geographical locations is introduced which together with a simple reservoir model allowed the assessment of impoundment based sites.

Chapter 7 presents the results of the modelling work carried out with estimates of potential run-of-river and impoundment hydropower potential under three discount rate scenarios. Separate figures are presented for scenarios featuring impoundment and run-of-river only to reflect the fact that development of impoundment sites may not be socially acceptable. The modelled results using future climate data are discussed.

Finally, Chapter 8 discusses the outcomes of the work and offers conclusions.

2
Literature Survey

2.1 Introduction

Hydropower uses available water developed as part of the hydrological cycle together with changes in elevation to produce power using water turbine generators. Hydropower is a mature technology with a history dating back to the beginning of the introduction of large scale electricity generation. As the availability of water for electricity production is dependant upon rainfall the resource is inherently variable. Suitability of sites for hydropower depend upon local geography and hydrology, making resource assessment essential to understand the potential of a site. Site design can be very complex as a variety of designs are possible depending upon the available resource and the desired operation of the scheme. In addition, sizing of a scheme must be carried out based upon a cost benefit basis to produce a financially optimal design.

2.2 Hydropower in Scotland

Hydropower has a long and emotive history in Scotland, with the first schemes constructed in the early twentieth century as a means to power aluminium smelters (Payne, 1988). The bulk of schemes for provision of domestic electricity were constructed by the publicly owned North of Scotland Hydroelectric Board (NSHEB) after the Second World War. Electrification of the Highlands was undertaken publicly as the sparse population would not offer enough revenue to a commercial enterprise. Hydropower was the chosen generation technology, as it would provide local employment and did not rely on the alternative of shipping coal, at large expense, from elsewhere in the country.

Hydropower development continued under the auspices of NSHEB until the late 1970s, by which point some 60 schemes had been constructed with a total capacity of over 1200 MW. With privatisation of the electricity industry NSHEB was incorporated then sold in 1991, ultimately becoming part of Scottish and Southern Energy (SSE), which still trades under the

Scheme / Grouping	Capacity (MW)	Commissioning Date	Operator
Affric/Beauly	176	1951-1963	SSE
Breadalbane	104	1957-1961	SSE
Conon	108	1950-1959	SSE
Great Glen	221	1955-1968	SSE
Shin	34	1954-1959	SSE
Sloy/Awe	262	1950-1963	SSE
Tummel	242	1930-1962	SSE
Galloway	109	1935-1936	SP
Lanark	17	1927	SP
Kinlochleven	20	1909	Alcan
Lochaber	84	1929	Alcan
Total	1377		
Pumped Storage			
Cruachan	400	1966	SP
Foyers	300	1974	SSE
Total	2077		

Table 2.1: Large historic Scottish hydro schemes (DECC, 2011b) (SSE, 2005)

name Scottish Hydroelectric. Whilst the bulk of Scotland's hydropower is found in Scottish and Southern's operational area in the North several large schemes are also located in the Scottish Power region to the South including the Galloway Hydros (109 MW) completed in 1929 to provide peak power for Glasgow and the Lanark Hydro's (11 MW) completed in 1927, situated near to the Falls of Clyde. The main schemes developed are shown in Table 2.1.

Figure 2.1 shows the cumulative capacity installed between 1910 and 2009, with a total of 1422 MW excluding pumped storage (BHA, 2010). The bulk of the capacity consists of the historic Hydro Board and Alcan sites (see Table 2.1). Very little development took place between 1963 and 2000, with only 30 MW of capacity commissioned during this period. Growth noticeably increases after 2000 with the development of the 100 MW Glendoe scheme in 2008 and 45 MW of numerous small hydro sites typically less than 2 MW in size.

There has been considerable interest in hydropower as a result of the introduction of the Feed in Tariff (FIT) with 59 MW of approved new schemes awaiting/undergoing construction. This number is increased further to 134 MW if the pumped storage improvements to the Sloy scheme are included. Scottish and Southern have released details of the planned development of two new pumped storage facilities at Coire Glas and Balmacaan totalling between 600 and 1200 MW in size located in the Great Glen (Lannen, 2010). When compared to the wind sector, the planned capacity for non pumped storage hydropower is small, with 3 GW of wind power consented or under construction as of December 2011 (Scottish Government, 2012).

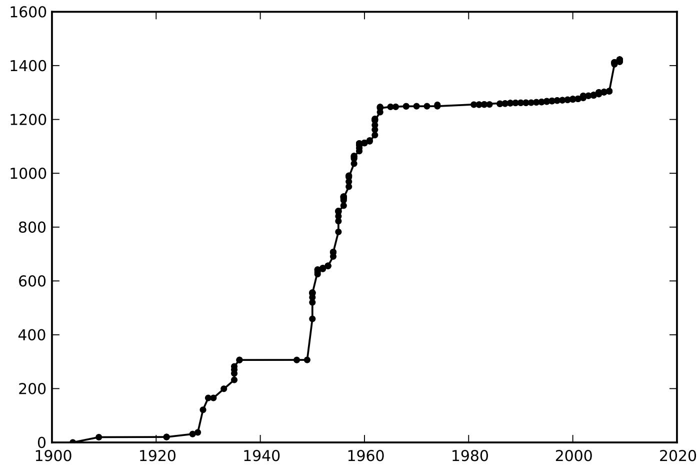

Figure 2.1: Scottish hydropower capacity constructed between 1900 and 2010

2.3 Characteristics of Hydropower

2.3.1 Generating Power from Water Turbines

Hydropower relies upon the conversion of potential energy of water based upon its mass and height to kinetic energy in a water turbine driving an electrical generator to produce electrical energy. The fundamental hydropower equation can be derived thus (Fritz, 1984):

$$P = \rho g Q H \tag{2.1}$$

where P is power (W), ρ is the density of water (1000 kg/m^3), g is the gravitational constant (9.81 ms^{-2}), Q is the flowrate of water into the system (m^{3}s^{-1}) and H is head (m).

The overall efficiency of these energy transformations is very high compared to other power generation, with water turbine efficiencies greater than 95% and hydraulic losses due to friction in penstocks typically less than 10 %.

It is common practice to calculate hydraulic losses in terms of a reduction in head or headloss. The headloss is deducted from the gross head to give net head. Additional electrical losses are introduced by the generator, step-up transformer and transmission losses before the Point of Connection (POC). Combined total losses of approximately 15% can be expected. Losses of efficiency can be included in the calculation of power giving:

$$P = \rho g H_{net} Q \eta_t \eta_e \tag{2.2}$$

where H_{net} is net head, η_t is water turbine efficiency and η_e is electrical efficiency.

When considering a scheme with variable flowrate and output power it is also necessary to consider how the change of flow will impact system efficiency. Hydraulic losses due to friction would be expected to fall as flowrate decreases, turbine efficiency varies across the design flow range typically peaking at 70% of rated flow, and electrical losses will vary with generated current due to transformer copper losses and line thermal losses. For schemes utilising a variable flowrate it can be seen that accurate assessment of output power and energy yield is more complex than suggested by simple application of Equation 2.1.

Hydropower schemes can be broadly categorised as high, medium or low head. High head schemes will typically be located in mountainous regions, utilising modest catchments and impoundment sizes but high elevation to achieve useful power production. Medium head sites typically use a high dam to store water and provide head for the scheme. Low head sites consist of a barrage type dam to create a modest head and develop power from large river flows. Different turbine designs have been developed to cater for the different configurations, catering for a range of heads and flowrates. A turbine selection chart is used to choose the correct turbine type for a site given its head and flow.

There are two categories of turbine design: impulse and reaction. Impulse turbines utilise the force of pressurised water hitting the surface of the turbine to produce mechanical power. The Pelton turbine is the most common turbine of this type consisting of a series of ‘buckets’ which are hit by jets of high pressure water created by a spear valve. The Pelton turbine is best suited to high head sites greater than 100 m and can operate at efficiencies of up to 97%. Turgo turbines are classified as impulse machines but have similarities to reaction machines. The Turgo turbine is used for medium head sites offering greater efficiency in the range between where a Francis or Pelton machine would be best suited.

Reaction turbines use the force of a continuous flow of water which changes pressure as it moves through the turbine giving up its energy. The most common reaction turbine is the Francis turbine which uses a spiral casing to direct flow onto the turbine runner. Guide vanes can be used to control the angle of flow allowing the turbine to operate efficiently over a range of flowrates. Kaplan and propeller turbines operate at low heads with large flow volumes; they feature very large surface areas and slow rotational speeds.

Turbine designs are easily scaled based upon the specific speed of the design. This is a dimensionless value that enables a design to be scaled to different flowrates. This enables manufacturers such as Gilkes and Gordon to offer a wide range of turbine sizes allowing an optimum fit to be made to the resource available at a site. This is significantly different from the wind industry where manufacturers will offer a much smaller range of tower heights and swept diameters, however it is possible to envisage a fully mature wind industry where turbines will have characteristics designed specifically for site conditions.

2.3.2 Installation Size

Interest in development of large hydro sites in Scotland has declined in recent decades due to lack of suitable sites and environmental concerns, one notable exception being the development of the 100 MW Glen Doe scheme. Focus has instead shifted towards the development of smaller scale hydro (SSH) sites. The definition of 'small' varies from country to country, however, an upper limit of 10 MW is widely accepted (Paish, 2002). No such arbitrary cut-off has been applied in this work, however the majority of identified sites are expected to be in the range below 10 MW in size, therefore this work will focus upon methods used for small hydro development. The design of SSH follows the same principles as large hydro schemes, with potential power calculated using Equation 2.1 with greater emphasis placed on turbine sizing as use of multiple units is less common and sites will typically operate as 'run-of-river' with variable inflows.

2.3.3 Run-of-River

Run-of-river generation is considered relatively benign environmentally as no land is flooded to create a reservoir and the obstruction to fish and other wildlife is greatly reduced compared to a dam. The resource is variable however as there is no potential for energy storage. A scheme will typically consist of a weir to divert water at the intake, channelled via a forebay tank to a penstock or power pipeline which drops to the power station over some distance.

To allow schemes to be designed in an optimum way it is necessary to have a good understanding of the flow regime. Traditionally this has been achieved through analysis of the flow duration curve developed from measured flow data at the site of interest and extended using data from nearby gauged catchments. Flow duration curves (FDC) are ideally developed from long term hydrograph records, typically around 30 years in length to account for climatic variations. Methods for sizing plant based upon the FDC are well established (Fritz, 1984; Penche, 2004; Warnick, 1984) and are also used to estimate energy yield. Although Scotland's river gauge network is widespread, many sites of interest will be located in ungauged catchments.

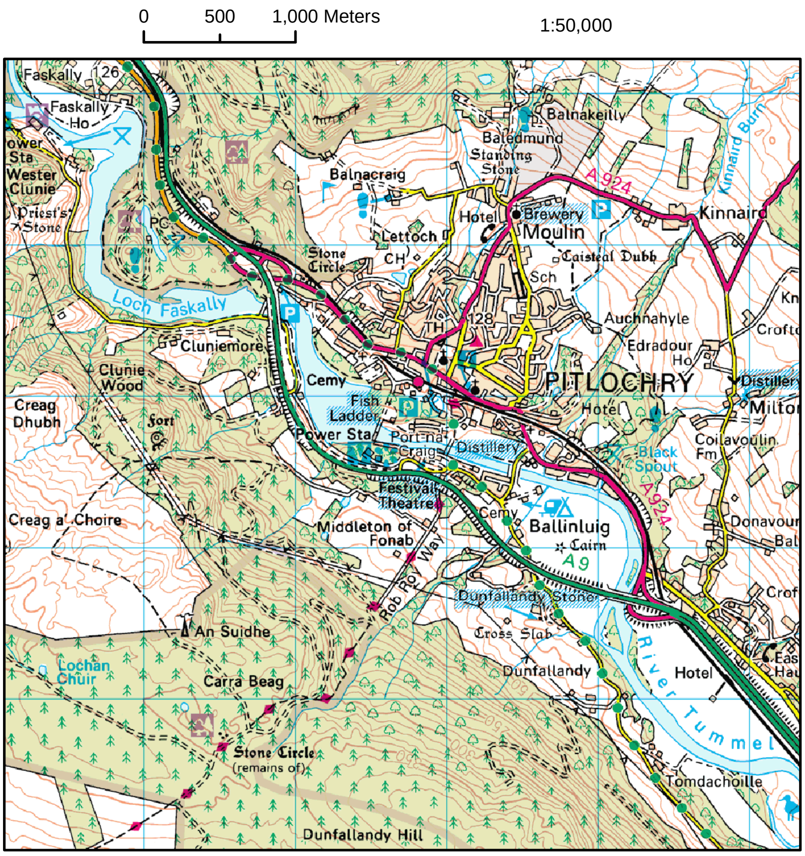

Figure 2.2: Pitlochry 15 MW low head run-of-river hydro Scheme

A number of run-of-river sites have been developed in in Scotland. The SSE scheme at Pitlochry developed by NSHEB in the 1960s is an example of an older low head run-of-river scheme that makes use of large river flows to develop useful power (see Figure 2.2). Comprising an unsubtle barrage type dam with an integrated fish pass, a gross head of 15 m is held behind the dam giving a rated power of 15 MW (SSE, 2005). As the dam completely interrupts the River Tummel's course the fish ladder is essential to allow movement of migratory fish upstream.

The RWE Innogy Black Rock site under development near Inverness provides an example of a typical modern run-of-river small hydro site (See Figure 2.3). Making use of reasonable river flows and a head of 91 m the site is rated at 3.5 MW. A diversion weir is located at the scheme intake which supplies a 3 km buried pipeline that roughly follows the route of the river before dropping to the powerhouse. This satisfies a major goal to limit environmental and visual impact. The use of a weir limits the effect upon water-life wishing to move upstream, as there is no inundation no land is lost due to flooding. Burying the penstock further reduces the visual impact of the site.

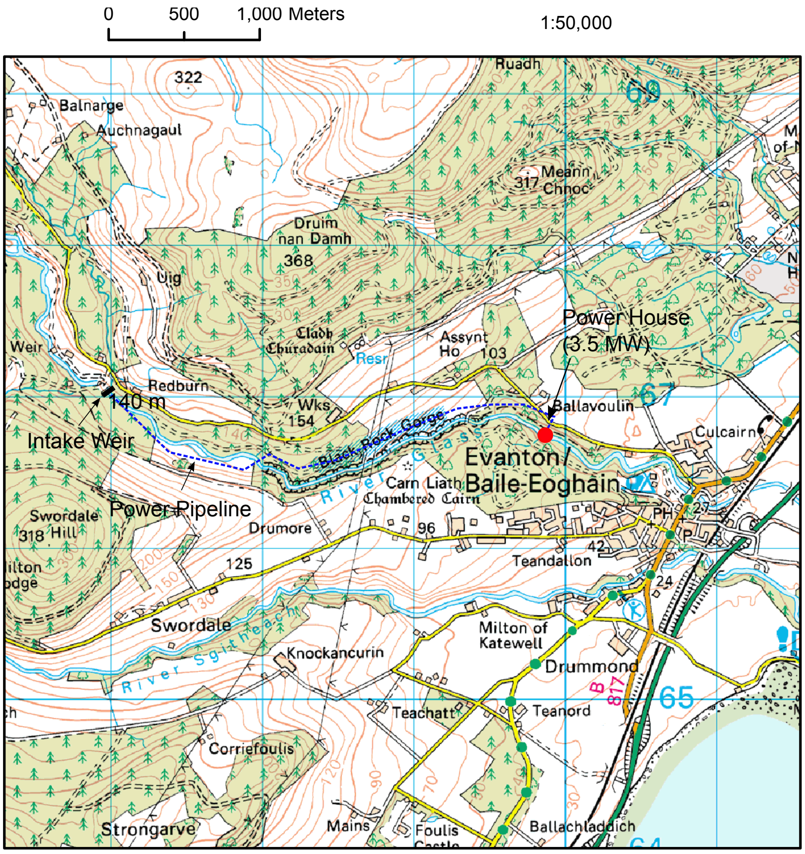

Figure 2.3: Black Water run-of-river hydro scheme

2.3.4 Impoundment

Impoundment schemes use a dam to store water which can then be released to generate power as required. Very large impoundments with sizeable catchment areas can be used to provide baseload power, the reservoir providing inter-seasonal storage. Smaller impoundments particularly at high head lend themselves to act as peaking plant whereby a volume of water is released during periods of high marginal price thermal generation. As the plant is operating typically less than 25% of the time it is then possible to oversize the plant compared to the resource as long as there is enough storage capacity to enable this and the difference between peak and average electricity prices is high enough to provide a sound business case.

The majority of large hydro schemes in Scotland utilise impoundment. The Finlarig scheme, a typical example, forms part of the Breadalbane group of SSE sites and is focussed upon the storage impoundment at the the high elevation Lochan Na Lairig (see Figure 2.4). Water is held back by the Lawyers dam which is 344 m long and 42 m high, the site makes use of the natural catchment feeding into the loch and extends this by use of a system of pipelines and aqueducts to take water from nearby catchments. The impoundment is located at an elevation of 521 m giving a gross head of 415 m. A power pipeline carries water down to the powerhouse on the shore of Loch Tay with rated power of 16.5 MW.

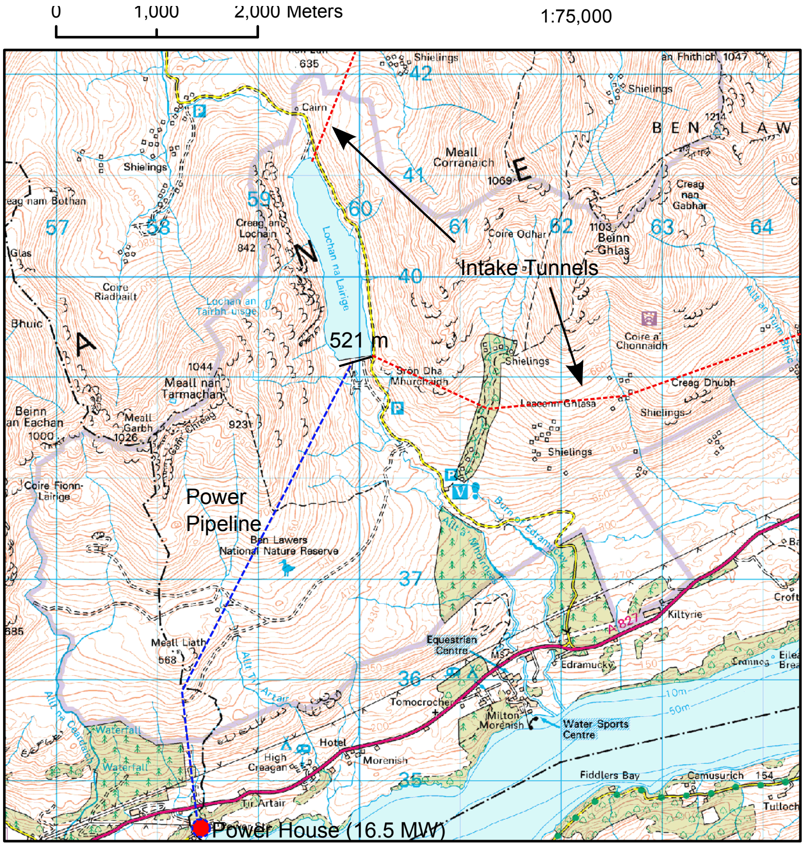

Figure 2.4: Finlarig 16.5 MW high head impoundment hydro scheme

2.4 Hydropower Resource Assessments

As hydropower relies entirely upon geography and hydrology, assessment of the available resource in a region can only be understood by analysing these features. Traditionally hydropower resource assessment has been carried out by performing labour intensive map analysis to identify catchments areas in regions with high annual precipitation large enough to produce useful flows and steep slopes to provide head. Identified sites would then be visited and further surveying undertaken. Developments in the availability of geospatial data and the tools to process them in recent years have enabled a new kind of automated hydro-resource assessment to be developed, reducing the need for map analysis while allowing large numbers of potential locations and site layouts to be trialled to identify the most financially viable sites. This section will summarise the resource assessments that have been carried out in Scotland and discuss others carried out elsewhere to further develop understanding of this research area.

2.4.1 Scottish Assessments

Four notable studies of Scottish hydropower potential have been completed over the past 3 decades producing capacity figures ranging from 286 MW to 1 GW for the remaining technically feasible and economic resource (Garrad Hassan, 2001; Nick Forrest Associates, 2008; Salford Civil Engineering Ltd, 1989; Scottish Hydro Electric Plc, 1993). A common feature of these studies, with the exception of the Salford study, is that only aggregate values for capacity and energy production are provided. No details of the location, layout or assumed design are given and the methodology is presented in very general terms. This together with a lack of site specific data makes it difficult to assess the robustness and credibility of the studies.

One study of Scotland's hydropower resource, with published methodology and detailed results, was undertaken by Salford Civil Engineering Ltd (1989). This study found Scotland to have 286 MW of potential in the 25 kW to 5 MW range. The study covers the whole of the UK with most effort spent on England and Northern Ireland. The reports terms of reference describe the run-of-river studies carried out in England and Northern Ireland as comprehensive. The study of Scotland's run-of-river potential is described as a preliminary desk study, with much greater resource required to carry out a full investigation of the economic potential.

Focusing upon small scale run-of-river schemes the study relied upon manpower intensive study of Ordnance Survey maps to highlight rivers with close contours, indicating useful head. The hydrological potential was estimated using regression equations, average evapotranspiration maps and standard annual average rainfall maps (SAAR) to calculate mean annual flow rate in m^3s^{-1}. Flow duration curves were then produced for each site using the Base Flow Index (BFI) method. This method utilises regression equations developed for each hydrometric area in the UK to select type flow duration curves based upon catchment BFI values. BFI was calculated using a regression equation from the Flood Studies Report based upon soil type within a catchment (NERC, 1975). No attempt is made to quantify the uncertainty of the soil type BFI regression model. The study was comprehensive in scope (the whole of the UK was studied) but, due to the labour intensive methodology, ultimately simple in approach (especially in Scotland) with no validation of Scottish findings carried out.

The Salford study was updated by renewable energy consultancy Garrad Hassan (2001) with the aid of Hydroplan, a specialist hydropower consultancy. The resource estimate comprised an update of sites identified by the Salford Study using modified environmental and economic constraints. An estimate of additional commercially sensitive resource was developed from Hydroplan's expertise, the location of which could not be specified. The study found 270 MW of resource based upon sites between 100 kW to 20 MW in size.

Scottish Hydro Electric Plc (1993) carried out a study analysing Scotland's renewable energy potential. A 3 year long map study was carried out to investigate the remaining hydropower potential. It was estimated that 1000 MW of practicable resource remained, although not all of this would be financially viable. Unfortunately no methodology or detailed results were published with the report.

The most recent assessment of Scottish resource was undertaken by Nick Forrest Associates (2008). Building upon methods developed as part of an MSc dissertation (Forrest, 2006) this work utilised a GIS based search algorithm to interrogate flow and elevation data at points along a river network derived from a Digital Elevation Model (DEM). Run-of-river schemes were trialled iteratively by placing a turbine then extending a penstock upstream until a satisfactory solution was found. Using this process 36,252 technically feasible sites were identified, these were then screened for financial viability. Assessment for the potential use of dams was carried out by analysing the terrain at the point of intake to identified sites, although details of how this was achieved are not included in the report. Financial viability was determined based upon net present value (NPV), with a site deemed viable if NPV was greater than zero after a 25 year operating period at 8 % discount rate. A final total of 1,019 potential schemes with total capacity of 657 MW and 2.77 TWh of energy production was found. Sensitivity analysis was performed for a range of factors affecting financial viability including discount rate, electricity sales revenue, required cost recovery period and several others. The most sensitive factors were found to be electricity sales revenue and discount rate.

There are few details in the report about the costing methodology used nor the cost data supplied by Black and Veatch; this is likely due to commercial sensitivity. Simple rules were used to assign design flow values to specific locations of 1.5 time mean flow for ROR sites and 2.5 times mean flow for impoundment based sites.

Assessment of the cost of connection was carried out using a mapped representation of the SHEPD and Scottish Power 33 kV networks. As no publicly available data exists for the location of 11 kV lines an assumption was used that clusters of 10 or more buildings would have access to an 11 kV connection. No details about assumed connection costs have been included in the report.

FDCs were developed using an analogue based approach from river flow data recorded at SEPA gauging stations. FDCs from each gauging station are assumed to have been scaled based upon catchment area and to provide estimates of flow at points on the river network. FDCs for ungauged catchments were estimated using data from nearby gauged catchments. The full details of the methodology used are not included in the report.

River reaches with existing hydropower development were excluded from the analysis, the impact of catchments feeding into existing schemes via aqueducts and tunnels was not accurately assessed and is highlighted as potential area for further work.

The methodology used in the study appears thorough and complete, however the lack of key details, unfortunately typical of consultant's reports, relating to the development of flow duration curves, assessment of costs and suitability of dams prevents a full critique of the study from being carried out. In addition only aggregate results by catchment are provided for installed capacity and energy production significantly limiting the value of this study and preventing a full assessment of the robustness of the results presented.

2.4.2 Assessments Carried out Elsewhere

A number of studies with varying levels of scope have been undertaken in other countries, the most ambitious being the study of hydro potential in the USA undertaken by Idaho National Engineering and Environmental Laboratory (Hall, 2007). This study utilised GIS and national datasets to compute the potential hydropower resource of every stream reach in the USA. Three dimensional representations of river networks were created using a digital elevation model and a national digital river network dataset. This allowed the head to be calculated between the upstream and downstream points of stream reaches. Annual average flow rates at ungauged stream locations were calculated using flow regression equations developed for each of the 20 US hydrological regions studied. The estimation of the available head and flow rate allowed the available water resource energy to be calculated in terms of the annual mean power. This analysis was then extended to investigate which sites could suitably be developed, and how much of the energy could be captured. A number of criteria were used to identify reaches suitable for projects including: a minimum project size of 10 kW, located out-with an exclusion zone such as a national park, within a minimum distance to a road and power infrastructure. Of the 500,000 water resource sites initially identified 130,000 were found to meet these criteria. The optimal position of sites within suitable reaches was then determined using assumed maximum penstock lengths.

A simpler GIS study of South African resource was undertaken by Ballance et al. (2000) by analysing slope values derived from a digital elevation model combined with digital maps of runoff. Available head was calculated using a 400m x 400m DEM, this was used to calculate steepness of slope from which the change in elevation across the cell was calculated. Available maps of mean annual runoff were used to calculate average flow across the the cells of the DEM by multiplying the cell area by the runoff depth. This allowed a simple assessment of hydropower energy density to be calculated on a cell by cell basis. This simple approach offers a useful tool to identify areas for additional study.

Kusre et al. (2010) carried out assessment of hydropower potential in the 2228 km^2 Kopili catchment in Northern India through a combined use of GIS techniques and flow data developed from the SWAT hydrological model. The SWAT model was calibrated for the catchment using available gauge data. Elevation data from a DEM was then used together with the simulated flow data to identify suitable hydro sites. The SWAT model was then run as required for these sites to produce 10 years of site specific discharge data which was used to create an FDC.

Using the computed FDC and calculated head, estimates of technical potential were made for locations with head greater than 10 m.

The studies discussed so far have all focussed, for the most part, on small run-of-river sites, Larentis et al. (2010) utilised GIS techniques to identify locations suitable for large impoundment schemes in Brazil. The method utilised ArcGIS to develop input data and display results, however the bulk of processing was carried out using external FORTRAN routines. The developed algorithms use a raster representation of the river network derived from a DEM. Locations for potential powerhouse, intake and dam locations can be determined automatically. This particular search algorithm is capable of fitting a dam to the available geography as represented by a DEM and then calculating reservoir inundation area and storage volumes behind the dam. The process is designed to be iterative so that the dam can be increased in height with the necessary lateral extension and the subsequent altered inundation and stored water volume recalculated and stored.

The majority of the approaches developed recently use GIS software to perform the bulk of data processing and analysis. It is notable that the iterative computationally intense methods used by Larentis et al. (2010) were performed using FORTRAN.

2.5 Economics of Hydropower

2.5.1 Costs

Hydropower schemes can be very capital intensive compared to conventional generation plant with levelised electricity costs largely influenced by discount rates as the majority of cost is upfront. In addition the costs are highly variable due to the site specific nature of hydro development (Table 2.2). Costs are exacerbated if a lengthy grid connection and access roads must be constructed.

Installed Costs (£000s/MW)	< 1 MW	1-5 MW	> 5MW
High	9507	4982	2858
Median	4481	2800	2307
Low	2797	2423	1448

Table 2.2: Hydropower installed costs in the UK for different scheme sizes (DECC, 2011a)

Hydropower however has very low operating costs, requiring little maintenance, and no payments for fuel (Table 2.3). Schemes typically have an operational lifespan of more than 50 years though this benefit is not accounted for using current project financial assessment techniques. Given the low operation and maintenance costs, fully amortized hydropower is a highly competitive source of electricity (Paish, 2002). Conversely, an assessment by Awerbuch (2008) shows hydropower to have a much higher financial risk than other generation types due to the uncertainty of construction cost estimates. Despite the wide range of typical costs it is normally assumed that capital costs fall with the size of scheme due to economies of scale.

Operating Costs (£000s/MW/year)	< 1 MW	1-5 MW	> 5MW
High	115	222	66
Median	42	81	54
Low	21	40	24

Table 2.3: Hydropower operating costs in the UK for different scheme sizes (DECC, 2011a)

The costs of renewable projects such as wind and PV can be estimated using a simple £/kW basis using data from turbine and panel manufacturers, with additional costs added for balance of plant and grid connection based upon experience from other projects. A hydropower scheme will use a combination of components from several suppliers and site specific civil works making assessment of costs much more challenging.

Ideally cost equations used for an assessment will be developed from data from recently completed projects, ideally in the same region, to get a true indication of development costs for a given location at a point in time. This is difficult to achieve as datasets will normally contain projects developed over a number of years, and in addition local costs of labour and materials are likely to vary. Together with the inherent variability in the costs of hydropower projects this will lead to a great deal of spread in the data used to calculate cost curves. Therefore they can only at best provide a rough estimation of costs.

To aid cost estimation empirical formula have been developed to allow rapid economic assessment of potential sites to be made (Kaldellis et al., 2005; Montanari, 2003; Wallace, 1989). Aggidis et al. (2010) developed empirical formulae to estimate costs of small hydropower projects in the UK based upon head and flow characteristics of a site. Data from turbine manufacturers was used to develop empirical cost curve formulae for Kaplan, Francis and Pelton turbines. Only electro-mechanical component costs were considered. As these form only a small part of the total costs of a project the method does not provide a complete way to calculate full project costs.

Building upon a body of work in this field (Gordon, 1981; Gordon and Noel, 1986; Gordon and Penman, 1979; Gordon, 1983) a series of Excel based tools called HYDROHELP has been developed by Gordon (2008) to enable pre-feasibility assessment of hydro schemes to be performed. These form the basis of the costing methodology used in the RETScreen software developed by Natural Resources Canada; a tool for analysing the financial viability of various types of renewable project including hydropower. A comprehensive hydropower financial model is included which uses empirical cost formula to allow estimation of project costs for all parts of a project.

2.5.2 Revenue

The UK electricity industry operates within a liberalised market framework. Because of this it is possible to trade electricity, taking advantage of higher prices during periods of peak generation. Variable renewable generators especially when not owned as part of a utility portfolio will usually enter into a long term power purchase agreement with a suitable buyer of electricity in return for a fixed price for electricity, assumed in this work to be close to the median market price. Dispatchable sites with impoundment have the ability to generate during peak hours only and hence receive a premium for this electricity by capturing higher market prices. An additional source of income is the Renewables Obligation (RO), the UK Government's flagship renewables support mechanism. It requires electricity suppliers to purchase a certain number of Renewable Obligation certificates from certified projects. The current value of a certificate is approximately £45. Hydro schemes less than 20 MW in size are eligible for this support. The current RO policy is being modified and is likely that support will be varied for different types of energy technology based upon its maturity, or some other criteria. A Feed in Tariff (FIT) was introduced in the UK for small renewable generators in 2010, the FIT is a simple price guarantee for production over a 25 year life varying with the size of the project.

2.5.3 Economic Optimisation

The bulk of literature concerned with the economics of hydropower is focused upon the optimal operation of large storage schemes given finite unpredictable inflows, varying electricity demand and other constraints such as maximum drawdown rates for environmental and safety reasons, public water supply and irrigation requirements (Garciagonzalez et al., 2007; Hamlet et al., 2002; Hreinsson, 1990; Labadie et al., 1987; Labadie, 2004; Mahmoud, 2004; Scott and

Read, 1996; Wang et al., 2004). Optimisation problems become extremely challenging when considering optimal operation of portfolio of plant or complex cascaded schemes and appear to have entered the canon of operational research as something of a classic problem. Forsund (2007) has developed a very thorough analysis of the economic operation of hydro schemes based upon the Norwegian hydro-dominated system. The analysis focuses upon the optimal operation of a very large portfolio of impoundment schemes.

There is a smaller body of work addressing the economics of new small hydro-sites, detailing methods to size scheme components to maximise economic benefit. Costs of penstocks and turbines vary significantly with design flowrate, however under-sizing either of these will limit yield leading to a need for cost benefit analysis to determine the optimum size. Voros et al. (2000) developed empirical equations of turbine efficiency curves and showed a generalised method for selecting economically optimal turbine size. Alexander and Giddens (2008) assessed the role of penstock sizing on small hydropower scheme economics. Anagnostopoulos and Papantonis (2007) demonstrated an optimisation procedure to correctly size project components for a given flow regime to maximise cost effectiveness of a small hydro project. A single high head run-of-river project was considered utilising two turbines. The design variable optimised included the type and design flow of the two turbines and the length and diameter of the penstock. Estimation of yield was carried out by extracting flow values from a flow duration curve of incoming flow and using these to calculate average power for different flowrates and the consequent annual energy yield taking into account variations in headloss and turbine efficiency across the flow range. The cost of scheme components including the penstock and turbine were calculated using an empirical costing formula enabling full financial assessment of different designs to be trialled. Optimisation of the site design variables to maximise NPV and energy yield was performed using an evolutionary algorithm. The two objectives were considered by assessment of the pareto front formed from the combined NPV and energy yield results for given trial simulations.

2.6 Environmental Considerations

A number of environmental considerations have to be made when designing hydropower schemes. Recommendations in Scotland are provided by the Scottish Environmental Protection Agency (SEPA) (Copestake, 2006). A minimum residual flow or “hands off” flow typically between 90th and 95th percentile flows (Q_{90} and Q_{95}) must be allowed to bypass the scheme to prevent drying of the riverbed. Additional freshets (controlled releases of larger volumes of water) may also be required. Schemes must be designed to allow the passage of migratory fish; this is a particular concern in Scotland due to the number of salmonid rivers that exist. Fish protection screens must also be used to prevent fish from being caught in turbines.

Release of water from impoundment schemes significantly alters the river flow regime and can effect the ecology of plant and animal life located downstream by altering the variability of water levels. Upstream of the dam significant changes to water residence times, oxygen levels and temperature can occur. Drawdown can cause scarring on the landscape due to erosion. The movement of sediment may also be altered. For these reasons impoundment schemes in Scotland operate with tight constraints on the rate and volume of drawdown to reduce the level of impact.

The consent process that a proposed hydropower scheme must enter depends upon its size with sites below 1 MW being the responsibility of local planning authorities and sites greater than 1 MW in size requiring Ministerial approval by the Scottish Government. This requires input from SEPA and other agencies including Scottish Natural Heritage (SNH). Projects are considered based upon the findings of an Environmental Impact Assessment which will consider the hydrological and ecological impact of a proposed scheme. A decision is made by weighing the likely impact against the social and economic benefits of the project. Copestake (2006) concludes that ultimate control of development of hydropower in Scotland rests with Ministers and therefore will depend upon prevailing politics when the balance is found between environmental impact and social and economic benefits.

2.7 Scotland’s Electricity Grid

The development of the UK’s high voltage transmission grid dates back to 1926 when the Central Generating Board was set up to interconnect generation assets to improve system efficiency and reduce the requirement for operating reserve to balance variable loads. The system was constructed based upon 132 kV lines and was extended to Scotland in 1929. The 132 kV system was expanded in the 1950s and 1960s to allow export of power from the NSHEB developed hydropower schemes.

From 1940s onward upgrade of the network to 275 kV was undertaken, with links a made to Scotland’s major cities in the Central Belt and on the East Coast. Upgrade of the network

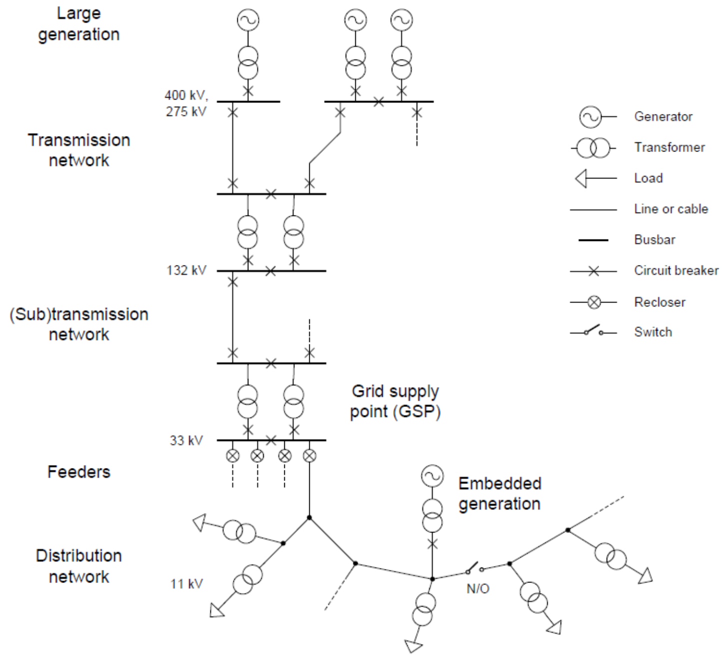

Figure 2.5: Structure of the Scottish electrical grid (Boehme, 2006)

in England and Wales to the 400 kV 'supergrid' began to take place in the 1960s allowing transmission of much greater amounts of power. The first 400 kV line built in Scotland was completed in 1972 to allow export of power from the Hunterston nuclear station to loads in the South. A 275 kV line was built in the North of Scotland to allow export from the experimental Dounreay reactor located near Thurso. A large proportion of Scotland's rural loads are supplied by the 33 kV and 11 kV distribution network. These are by far the most extensive networks available in the highland and west coast regions where population density is sparse. A schematic of the current grid structure is given in Figure 2.5 and its geographic spread in Figure 2.6.

The distribution network in rural Scotland consists of long radial lines, a number of which will span out from a primary substation at 11 kV to supply dispersed domestic loads. Losses on the 11 kV system are high especially when the lines distance exceeds 2 km, this makes them unsuitable for connection of larger hydro generation that will require export capacity. Losses on the 33 kV system are more acceptable and it is possible to connect fairly substantial embedded hydro generation with acceptable levels of losses.

Ideally when assessing the potential for an embedded hydro scheme a network integration assessment would be carried to assess the cost of any necessary network reinforcement and ap-

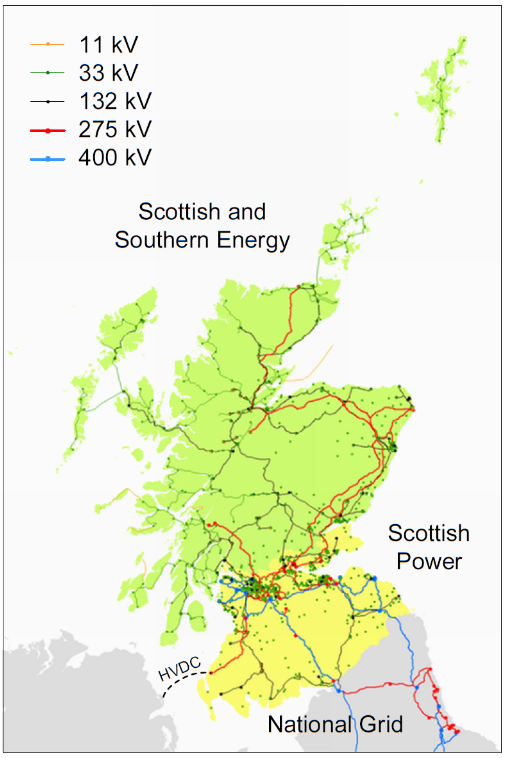

Figure 2.6: Geography of the Scottish electrical grid (Boehme, 2006)

portion this to the cost of site development. This is a non-trivial task that requires a detailed model of the Scottish distribution system that could be used to assess the impact on system voltage and thermal limits. To simplify the assessment of grid connection the assumption has been made in this work that all generation will be able to connect without incurring the cost of additional reinforcement (Boehme, 2006).

2.8 Topography of Scotland

Scotland has the largest areas of uplands in the UK with over 70% of land area lying above 100 m and 30% lying above 300 m (see Figure 2.7). The highest peak, Ben Nevis, located to the west near Fort William rises to 1344 m. There are several significant mountain ranges including the Cairngorms, Grampian and Trossach regions which lie North of the Highland boundary fault which divides the country into the Lowland and Highland regions. The upland Highland areas characterised by wet steep slopes are the source of much of Scotland's hydropower resource, although the Southern Uplands in the borders region also offer useful potential. Most of the country's population and hence electrical load is located in the Central Lowlands, notably

Glasgow and Edinburgh.

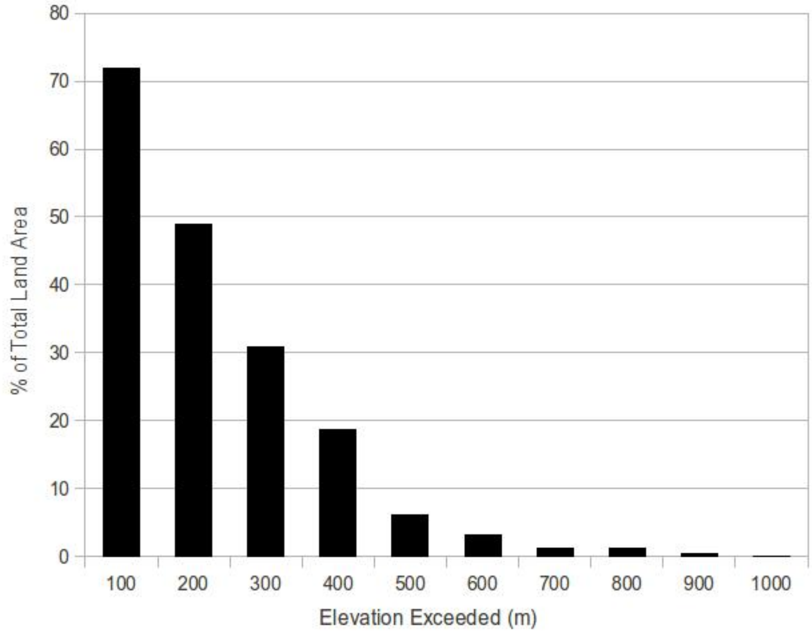

Figure 2.7: Distribution of elevation

Scotland is a well mapped country with several quality data sources available detailing the topography and suitable for use in a hydropower assessment. The most important depository in terms of this work is the Edina service which provides access to Ordnance Survey (OS) data for academic research.

Digital Elevation Models provide a 3D representation of surface terrain, usually consisting of 2D arrays of height values, although DEMs constructed using vector based triangular irregular networks are also available. Several DEMs are available that provide full coverage of the UK. The OS Profile product is derived from 1:10,000 scale contour lines interpolated to 10m resolution, while the lower resolution OS Panorama product is derived from from 1:50,000 scale contour lines. Both OS products have vertical accuracy of +/- 0.5 m. NEXTMap have developed the 5 m resolution NEXTMap Great Britain DEM using Interferometric synthetic aperture radar (IFSAR) technology, this is currently the most accurate representation of UK terrain with a vertical accuracy of +/- 50 - 100 cm, however the storage requirements are significant with Scottish coverage totalling 100 GB of data (Chiverrell et al., 2008). The topology of Scotland as generated by a DEM is given in Figure 2.8.

OS maps are available at various scales, however the OS Landranger 1:50,000 product is very

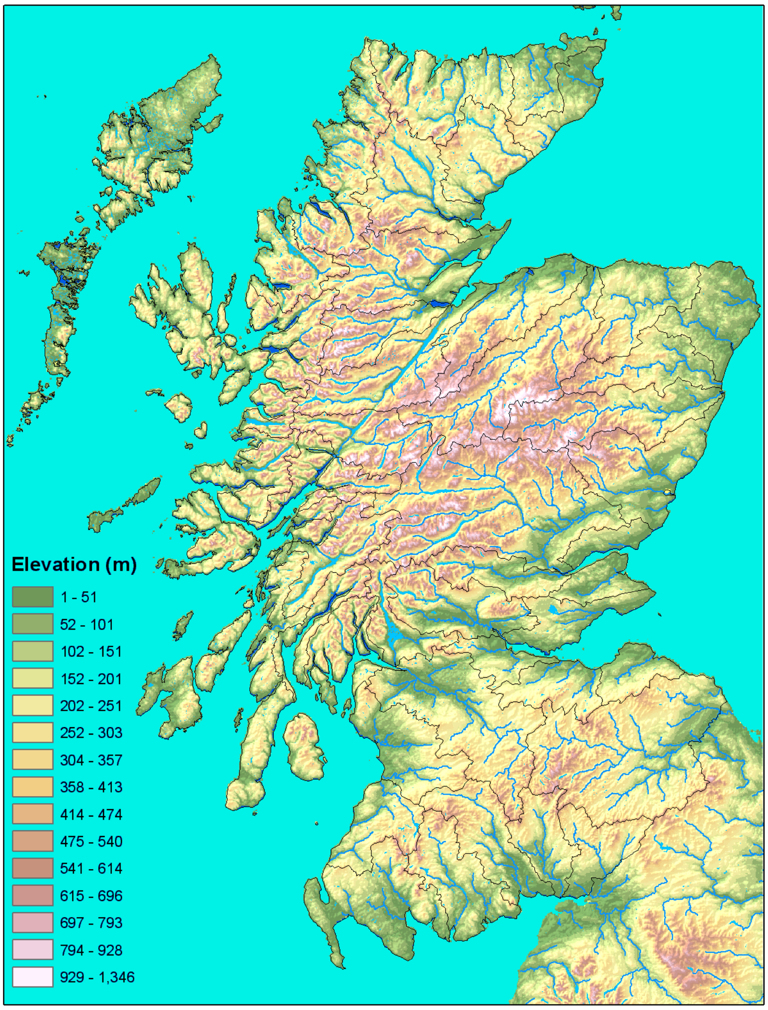

Figure 2.8: Elevation in Scotland

detailed, with dams, weirs and old mill sites all represented. Unfortunately this is only available in an unsearchable raster format. The OS Mastermap product is the most advanced, covering the UK in a range of scales in a searchable vector format; unfortunately access to this dataset is limited.

2.9 Hydrology

2.9.1 The Hydrological Cycle

Hydrology is a very wide field, concerned with large scale processes such as the movement of fresh water on a global scale and very small scale processes such as the transpiration of individual plant species. At its most general the science concerns itself with the elements that make up what is known as the hydrological cycle which is a useful starting point for discussing the subject.

The hydrological cycle describes the movement of water between land, sea and the atmosphere. Water is evaporated from the sea by the sun then transported by weather systems as cloud. When a weather front reaches land, hilly country in particular, the moist air forming the front is lifted causing the moisture to condense into water droplets and fall to the earth's surface as precipitation. When the precipitation reaches the ground the role of local soil type, vegetation, geography and climate will determine the subsequent movement of the water. If temperatures are low, ice and snow may remain on the surface, otherwise the water will enter groundwater where it may remain for thousands of years or move over the land surface to form streams rivers and lakes which will transport water to the sea. Evaporation will return water from the soil and surface water to the atmosphere either directly or through the transpiration of vegetation (Ward and Robinson, 1999).

2.9.2 Catchment Water Balance

Practical hydrology is most commonly interested in the function of river systems consisting of a single large catchment or a number of smaller catchments that converge. The movement of water within a catchment can at its simplest be described as a water balance where:

$$Outflow = Inflow \pm \frac{\delta(Storage)}{\delta t} \tag{2.3}$$

Inflow takes the form of precipitation; rainfall and snow. Outflow can take the form of evaporation, transpiration and surface runoff, while storage exists in lakes, rivers, snowpack, glaciers, soil moisture and groundwater. Given a sufficient length of time, typically a year, it can be assumed that water held in store will be fully discharged and recharged and therefore sums to zero. This allows the water balance of the catchment to be estimated from precipitation measurement, evapotranspiration measurement and discharge measurement. Given a catchment area a balance can be made between these components in terms of a specific annual depth, usually measured in mm:

$$Q = P - ET \tag{2.4}$$

where Q is catchment discharge, or stream flow, P is precipitation and ET is evapotranspiration. Groundwater recharge is another potential loss factor that has been omitted here; this depends upon the nature of aquifers located within a catchment. If it is possible to close the water balance then the resulting movement of water within a catchment can be understood. Unfortunately it is difficult to close the water balance equation using values measured by instruments due to uncertainties in measurements and difficulty of using point measurements to represent catchment scale processes (Beven, 2003).

2.9.3 Rainfall

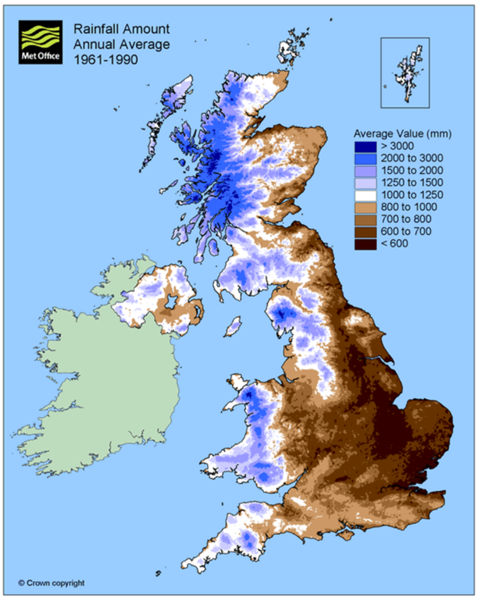

Figure 2.9: Rainfall climate for standard period 1961-1990 (UKMO, 2011)

Scotland is a wet country especially in the North and West where prevailing winds blow moist air onto large upland areas that force the air upwards causing high levels of rainfall. Between 3000 and 4000 mm of annual rainfall is common over large areas of upland Scotland. These are the areas where the majority of existing hydro sites are located (Payne, 1988).

Average annual rainfall is used to represent the expected rainfall for a given location and is calculated based upon a 30 year average, usually 1961 - 1990 or 1971 - 2000. It is common practice for meteorological organisations such as the UK Met Office (UKMO) to develop mapped climatologies of rainfall such as the one shown in Figure 2.9. The standard annual average rainfall (SAAR) map developed by CEH Wallingford details average rainfall across the UK at 1 km^2 resolution. The averages are based upon measurements and observations made during the standard meteorological period 1961 - 1990, and are assumed to be computed using an isohyetal method.

The complete MET Office archive of land station data is available from the British Atmospheric Data Centre (BADC) for bona fide academic research. The most critical for hydrological analysis is rain gauge data. The UKMO operates a substantial network of daily rainfall gauges and a much smaller network of hourly recording gauges with records for the last 50 years. Gauges tend to sparse in areas of arduous terrain and sparse population such as the Scottish Highlands however and there are often gaps in the record. Ideally a catchment hydrological study will utilise a number of rain gauges located within the catchment to allow areal precipitation to be accurately calculated. In practice it is not uncommon to need to interpolate values from a number of nearby gauges to infill missing data from the gauge closest to the catchment of interest.

To overcome these problems a number of techniques have been developed to produce estimates of areal rainfall from datasets of point rainfall data. Traditional techniques include Thiessen polygons and isoheytal techniques. These have been superseded by interpolation techniques such as inverse distance weighting and advanced geostatstical techniques including kriging and thin-plate-spline methods which may offer greater modelling skill. Also of importance is the development of methods that use multivariate statistical relationships to incorporate terrain characteristics and other meteorological variables.

Radar generated precipitation data covering all the UK from 2003 onwards is available from the UKMO via the BADC. The radar return is calibrated using gauge data, so it can be seen as a highly sophisticated form of interpolation. 15 minute time resolution data is available at 1km and 5km spatial resolution, the length of record is short, currently limiting the value for hydrological analysis of flow regime, however in future it will be a valuable resource. One limitation of radar data is that the return is affected by terrain, with accuracy reducing in areas shadowed by hills for example.

2.9.4 Evapotranspiration

The evaporation of water from soil and transpiration from plant leaves forms the process known as evapotranspiration. The main drivers of this process are solar radiation and air temperature, the main sources of energy for evaporation. Other factors include the ability of the air to transport evaporated moisture from soil and plant leaves which depends on humidity levels, wind speed and plant physiology.

Potential evapotranspiration (PET) is a term used describe the evapotranspiration that would occur if there were no limitations to available water held within soil. Actual evapotranspiration (AET) is the evapotranspiration that occurs when limitations to soil moisture are considered.

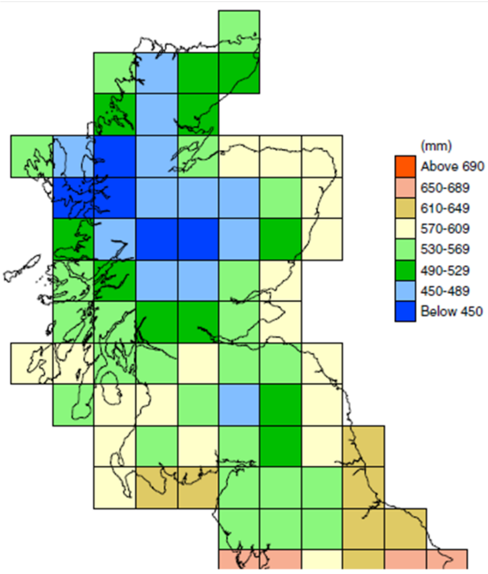

Figure 2.10: Actual evapotranspiration total for 2010 (CEH, 2008b)

There are several methods for calculating evapotranspiration varying in physical completeness and data requirements, with the most complete being the Penman-Monteith method. The UKMO provides estimates of evapotranspiration from the MORECS system (Hough and Jones, 1997) which uses meteorological station data interpolated to a grid to calculate PET and AET using the Penman-Monteith formula incorporating land use classifications and a soil moisture model (see Figure 2.10 for an example). The FAO 56 Penman Monteith method (Allen, 1998) is widely applied using gridded datasets and provides a complete method including standard values that can be used to represent different types of crops and vegetation.

2.9.5 Discharge

Measurement of river discharge is carried out using gauging stations that make an indirect measurement of river flow based upon the height of the river at the point of the station. This is normally achieved using a weir or flume structure with a consistent geometry that improves consistency of height measurements. As the water level is an in-direct measurement it is necessary to convert this into a measurement of water volume. This is achieved using a rating curve that relates height to volume. The rating curve is developed by taking measurements of water velocity at different water levels and a measurement of the channel geometry to determine the cross-sectional area allowing a calculation of flowrate to be made (Maidment, 1993).

Scotland's rivers are monitored by a number of SEPA operated river gauges, with time series of at least 30 years available for each gauge available from the National River Flow Archive as daily average flow measurements.

CEH Wallingford has developed a digital river network of the UK, derived from OS maps. The river network is very comprehensive and structurally accurate; however there is reasonable alignment error (approximately +/- 20m) which becomes apparent when the network is overlaid on OS 1:50,000 scale maps.

2.9.6 Hillslope Hydrology

The processes governing the movement of water within Scottish catchments can be described by hill-slope hydrology. To further investigate the development of surface flows it is necessary to adopt a conceptual model of these processes. There are numerous conceptual models, and as Beven (2003) describes, these are dependant on several factors:

> Hydrological systems are sufficiently complex that each hydrologist will have his or her own impression or perceptual model of what is most important in the rainfall - runoff process, so different hydrologists might not necessarily agree about what are the most important processes or the best way of describing them. There are sure to be general themes in common, as reflected in hydrological texts, but our understanding of hydrological responses is still evolving and the details will depend on experience, in particular the type of hydrological environments that a hydrologist has experienced. Different processes may be dominant in different environments and in catchments with different characteristics of topography, soil, venation and bedrock.

The conceptual model used in this work is based upon Beven (2003) and Ward and Robinson (1999) and is assumed to be a representative model of typical hill-slope hydrological processes found in Scotland (Figure 2.11).

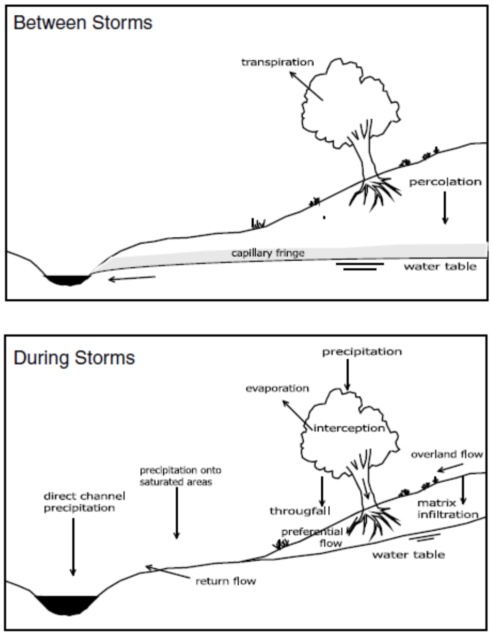

Figure 2.11: Conceptual model of hill-slope hydrology (Beven, 2003)

The majority of precipitation that reaches the ground surface is absorbed by soil, a process known as infiltration. The remainder will flow quickly as overland flow to nearby streams. Water that has infiltrated into the top layers of soil will be subject to evapotranspiration and will flow close to the surface as throughflow. Depending on local conditions a proportion will percolate under gravity to form groundwater.

The level of ground water is commonly refereed to as the water table and indicates that sub-surface layers are saturated, that is the pores of soil and fractures in rock formations making up these layers can hold no more water. Layers that are permanently saturated are referred to as the saturated zone. The water table will rise and fall depending on the amount of water that has infiltrated the top layers of soil and percolated downwards and the amount of water leaving the saturated zone and returning to the surface. The layers that are saturated for only a proportion of time are termed the intermediate zone.

Soil water is the water stored in soil above the water table, this can include all layers in the unsaturated zone. Of most importance, from a hydrological point of view, are the soil layers closest to the surface as the ability of these to retain water has a large impact on the generation of quickflow within a catchment. In catchments with thin soils located on top of rock, or with impermeable soils rainfall rapidly runs off the land as quickflow. During heavy periods of rainfall the soil can become saturated again leading to generation of quickflow.

Runoff is the term given to rainfall that 'runs off' land within the catchment into channels forming streams and rivers. Runoff can be considered to be transported by several flowpaths, direct precipitation onto surface water, overland flow, shallow subsurface flow (throughflow) and deep subsurface flow (groundwater). Overland flow consists of water that moves very close to the soil surface towards streams, the formation of overland flow can be attributed to the limited ability of water to infiltrate the soil due to high intensity of rainfall or low soil infiltration capacity. This process is especially evident in arid areas with little vegetation whereby intense rain causes the formation of crust on the topsoil limiting infiltration. If the water table is very close to the surface prolonged rainfall will cause the water table to rise to the surface causing all soil to be saturated leading to saturated overland flow.

Water that has infiltrated the soil can move laterally towards nearby streams as throughflow. This tends to occur after rainfall when vertical movement of water through the soil is limited. As hydraulic conductivity tends to be greater in layers closer to the surface the movement of water as throughflow is a common mechanism and is even more pronounced if a thin soil overlays an impermeable bedrock. Throughflow is particularly associated with upland headwater catchments where the role of gravity on steep slopes leads to lateral movement of water through soil layers near to the surface. A useful analogy is that of the thatched roof. Straw is in no way waterproof with a high infiltration capacity, however it can still be used as an effective roofing material due to its ability to laterally transport water when laid on a slope. Rainfall falls on to the thatch and then follows the path created by the aligned individual straws. There is a preferential flow along the the straw rather than vertically down through the straw into the building. If the thatch were laid flat and no longer at an angle this process would no longer occur and rainfall would infiltrate the thatch until it became saturated.

Further downstream from the headwaters streams converge to form rivers. At the base of valleys slopes become shallower so less throughflow is developed and water will percolate into the subsurface groundwater. Water will will reach rivers as slow groundwater flow. As the movement of the groundwater is very slow compared to throughflow the contribution from groundwater will usually occur some time after the precipitation first fell into the catchment and entered the groundwater, usually measured in days or weeks. The contribution of groundwater is generally very consistent as it represents the slowly changing levels of stored water held deep within the catchment.

A typical catchment area hydrograph will have periods of baseflow associated with periods of low precipitation and short periods of greatly increased flows when heavy precipitation is experienced. The rapid response of the hydrograph to precipitation shows that a proportion of rainfall will move rapidly into surface channels as quickflow; the presence of baseflow shows that a proportion takes a slow route to form surface runoff (see Figure 2.12).

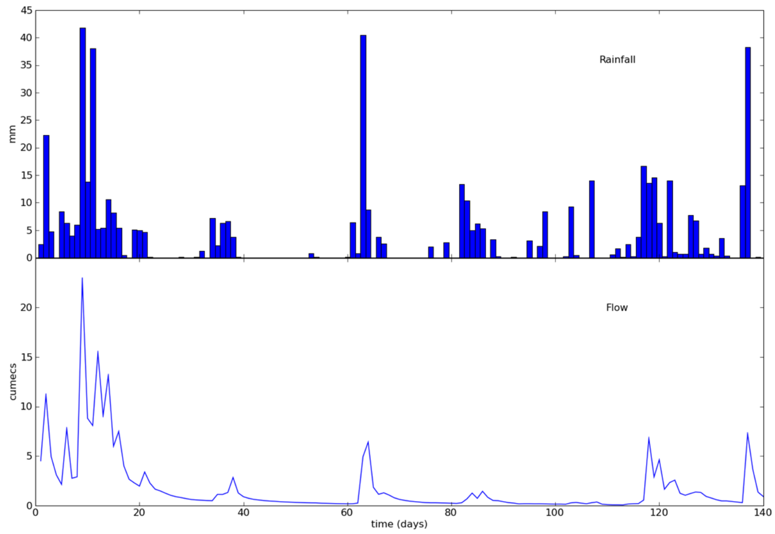

Figure 2.12: Catchment response to rainfall

In addition to hill-slope hydrology, the role of groundwater held in aquifers is an important consideration. Layers of material with sufficient porosity to hold large volumes of water are commonly referred to as aquifers. Aquifers that are in part close to the surface and therefore unconfined will be recharged by rainfall. Deeper confined aquifers will contain much older water and recharge rates may be very slow.

2.10 Hydrological Modelling

2.10.1 Development of Computer Based Hydrological Models

The need to accurately predict river flows based upon measured rainfall has spurred the development of a range of modelling techniques ranging from very simple empirical models to sophisticated distributed models governed by physical equations.

There are two main approaches to hydrological modelling. The first views modelling as a tool for extending the use of available datasets to allow more complete hydrological analysis, where there is interest in ungauged catchments or risk of infrequent flood events for example. This type of approach is usually practised by engineers who require suitable design values for civil structures such as bridges. The second is focused on developing models which encapsulate the current knowledge of the physical process involved in the hydrological cycle in order to test and extend this knowledge. This is the realm of hydrological science and academic research.

The first approach has led to the development of many 'unashamedly empirical' (Beven, 2003) hydrological techniques, where the goal has been to develop a tool of practical value. The ASCE Hydrology Handbook (Maidment, 1993) describes a variety of empirically based techniques to allow design parameters such as storm frequency and runoff to be calculated from available data.

Initial development of computer based models was confined to academia; computer based physical models such as the pioneering Stanford Watershed Model, utilise a number of stores to represent the different catchment processes with linking equations controlling the flow of water between the stores, a so called lumped conceptual model, to describe the characteristics of a hydrological system (Singh and Frevert, 2006). As computational power increased development of distributed models became feasible. Freeze (1969) described the potential for distributed models, utilising a grid structure populated with different parameter values with calculations performed on each cell. A direct implantation of this framework was the Systeme Hydrolgique European (SHE) (Abbot et al., 1986) which attempts to describe catchment hydrology using physical equations on a gridded catchment representation.

2.10.2 Available Hydrological Models

Hydrological models have been deployed to study numerous problems, such as assessing peak flow during storms (Chancibault et al., 2006), understanding the distribution of pollution and the movement of sediment and of most interest to this project, estimation of stream flow based upon rainfall. Different temporal and spatial resolutions can be used, largely depending upon data availability and the goals of the modelling exercise. Exercises in the literature range from extensively instrumented experimental catchments (Johnson, 1995) to national hydrological models (Henriksen et al., 2003). Consequently a large number of models have been developed, a selection of the most popular have been assessed by Singh and Frevert (2006), Singh and

Woolhiser (2002) has also briefly reviewed a very large number of models (over 100) attempting to categorise their features. The majority of models operate at a daily resolution although monthly water balance models are also common (Nützmann and Mey, 2007; Xu and Singh, 1998).

Models can be categorised as lumped or distributed. Lumped models are relatively simple to use, generally with fewer parameters and modest computational requirements when compared to distributed models. They are limited however as they can only be used to predict flows at a single point where calibration has been performed. Distributed models by their nature are capable of predicting flows for all modelled surface channels within a catchment. In terms of developing a suitable model to predict flows for use in a hydropower resource assessment the distributed model has a distinct advantage.

Model	**Description**	**Number of Parameters**
Stanford Watershed Model (Crawford and Linsley, 1966)	Lumped, conceptual	up to 35
SHE (Abbot et al., 1986)	Distributed, physical	17
Topmodel (Beven et al., 1995)	Physically based, semi distributed	7
HBV (Lindstrom et al., 1997)	Lumped, conceptual	29
IHACRES (Croke and Jakeman, 2004)	Lumped, empirical	5 to 7
G2G (Bell et al., 2007a)	Distributed, conceptual	8 to 10

Table 2.4: Some available hydrological models

Models can be further categorised as either empirical, conceptual or physical. Empirical models use relationships, such as regression equations or transfer functions, between input data, such as rainfall and evapotranspiration and measured catchment response data, normally daily or sub-daily river gauge data without considering the physical interaction of the measured values. The parameters describing the relationship are calibrated using the measured data to allow the model to make further predictions. Physical models such as SHE use physically based equations to describe catchment processes derived from laboratory and field measurements. The governing equations tend to be non linear partial differential equations which are solved using a finite difference scheme, as such the computational requirements of these models are typically very high. Distributed physical models typically have a very large number of parameters, due to to the use of a grid structure, that can either be determined based upon measurement or through calibration. Conceptual models lie in between, tending to utilise simplified mathematical representations of the physical processes while trying to stay true to the hydrologists' conceptual model of catchment behaviour.

2.10.3 Distributed Hydrological Models Used in Scotland

Several models have been used in Scotland. TOPMODEL (Beven et al., 1984) is a semi distributed conceptual model that analyses topographic variability of a catchment to determine the effect of gravity on hill-slope water movements to improve predictions of quickflow. Cameron (2006) used TOPMODEL together with UKCIP02 climate change data to investigate the changes to flood events for a catchment in North East Scotland. DIY is a distributed model developed by Dunn and McAlister (1998) and applied to the Ythan catchment in North East Scotland.

Hydrological modelling studies carried out in the UK tend to focus at most on no more than three catchments presumably due to time consuming data preparation and limiting computational requirements. The only distributed model that has been applied widely in the UK is the G2G model developed by Bell et al. (2007a,b) to investigate climate change impacts on flooding.

2.11 Climate Change Impact on Water Resources

Projections of climate change made using global circulation models (GCM) show that globally precipitation is expected to increase, however locally there are large variances due to changes in circulation. Evapotranspiration is expected to increase almost everywhere because the water-holding capacity of the atmosphere increases with higher temperatures (Intergovernmental Panel on Climate Change, 2007).

Lehner et al. (2005) investigated the potential impact of climate change on available European hydro resource using a global scale hydrological model forced with output from global climate models to calculate run-off. The results of this work suggest that precipitation will significantly increase in Northern Europe, with similar order reductions in runoff experienced in the south. It was concluded that the potential output from hydropower is likely to increase in Northern Europe.

Bergström et al. (2001) Produced scenarios of change to runoff under future climate change using a combination of global circulation models (GCMs) and a regional climate model to produce meteorological data that was used with the HBV hydrological model. The impact on hydropower production and dam safety was considered. Hydrological modelling was carried out for 4 catchments with large hydropower developments. In general it was found that water resource would become more abundant in the north and major changes to snowmelt patterns would make melt-water less predictable. Considerable impacts to design floods due to intense rainfall suggests implications for dam and spillway designs

Harrison and Whittington (2002) combined a water balance model with a reservoir model, electricity market model and financial model to enable financial assessment of hydropower schemes under future climate to be made. The method was demonstrated for a case study project; the 1400 MW Batoka Gorge project located on the Zambezi river in Zambia. The energy yield and financial performance of the modelled scheme was found to decline under a future climate.

To aid applied use of climate model projections the UKCP09 project utilises a Regional Climate Model (RCM) to produce probabilistic projections on a high resolution 25 km grid for the UK (Murphy et al, 2010). The RCM is run numerous times for different emission scenarios using different GCMs to provide boundary conditions. It is thought that incorporating the range of uncertainty into projections will enable more robust risk based decisions to be made. The probabilistic projections are provided in terms of Bayesian statistics and presented as a CDF of values with associated probability values. When referring to the results it is recommended that projections at a minimum are provided in terms of the 10%, 50% and 90% levels.

The UKCP09 Weather Generator uses the probabilistic projections to perturb a stochastic weather simulator that is capable of producing daily time series representative of future climate for a chosen grid square (Kilsby et al., 2007).

2.12 Geographical Information Systems

Geographical Information systems (GIS) are tools that allow spatial data to be processed into useful information with which to support decisions made concerning a particular geographic area.

ArcGIS developed by ESRI is the current market leading system and is in widespread use in the research, commercial and public sectors. Alternative open source applications, most notably GRASS which is included as part of many popular Linux distributions, are gaining support in the research sector (Neteler and Mitasova, 2002).

Arc Hydro is an extension available for ArcGIS which enables the user to create a hydrological geodatabase either from a digital elevation model or an existing digital river network (DRN) (Maidment, 2002). The geodatabase assigns what is termed a ”hydro id” to each reach in a river network and creates nodes at the end of each reach to allow connectivity to be fully categorized. The toolkit can be used to define the boundary of catchments and associate them with relevant sections of the DRN.

A major problem with desktop GIS packages is the limitation to a single machine’s memory and processor. This becomes particularly apparent when iterative processes such as the use of time series of 2D rasters is attempted. In addition commercial GIS packages such as ArcGIS operate a single desktop licensing model, whereby a single license allows use of the software on only one windows machine. The limitations of desktop GIS systems have led to the development of “roll your own” GIS approaches, whereby the core functionality of GIS software, 2D array processing, and database analysis are replicated using high performance database packages and custom analysis code written in FORTRAN, C, C++ or Python.

A key tool allowing this analysis is the Geographical Dataset Abstraction Library (GDAL) (Warmerdam, 2008). GDAL provides the necessary tools and functions to allow typical GIS raster formats to be loaded into a 2D or 3D array structure implemented in a language of choice. Custom processing functions can then be developed to operate on the data. Use of this approach enables vastly greater computational efficiency compared to the use of Desktop GIS as the codebase is inherently leaner and can be optimised to suit the data being analysed and allows the creation of true grid based environmental models. Final results can be saved from the array to a suitable GIS format and desktop GIS used to present final results.

2.13 Problem Statement and Overview of Methodology

To enable an accurate assessment of Scotland’s existing and potential future hydropower resource to be developed it is proposed that a spatial-temporal resource model be developed to generate time-series river flows represented on a geographical grid. This has been carried out by Bell et al. (2007a) to investigate flood risk. Boehme (2006) undertook an investigation of other renewable resources, taking into account the timeseries spatial resource and constraints such as connection costs. Harrison and Whittington (2002) developed methods to assess the financial performance of hydropower schemes under a future climate. Forrest (2006) developed an approach for assessing micro-hydro projects utilising GIS methods and multiple trials of scheme layout. The methodology presented here builds upon this work. A key driver for the assessment is the need to be able to future proof the methodology to allow more up to date climatological data to be incorporated and to be able to project future resource levels as the climate changes in the coming years. To deliver this a substantial modelling effort has been carried out to deliver the following methodology.

The method is based around an enhanced high resolution implementation of the G2G model that allows long-term time series of river flows to be simulated at regular intervals across the network of Scottish rivers. The addition of a simple snowmelt model improves the applicability to the high elevation Scottish catchments where snow accumulation and melt significantly affect hydrology. Chapter 5 describes the enhanced model and its extensive validation. A schematic of the hydrological model, its constituent parts and the extensive data sources that feed it are shown in Figure 2.13.

Inputs to the model are in the form of gridded meteorological time series. These include gridded rainfall data derived from UK Met Office raingauges and an interpolation procedure based upon thin plate splines; evapotranspiration estimates using the FAO 56 Penman-Monteith method was derived from UKMO 5 km datasets and the European ENSEMBLES data. The development these data sources are detailed in Chapter 3. Underpinning the hydrological model is a new river network dataset developed using the ArcHydro model. This provides a system to network rivers and enables interrogation of the network in a hydrologically consistent way (see Chapter 4). Elevation data from a 10 m DEM is assigned at regular points along the river database and the river database is linked to gridded flow time series, providing the necessary head and flow data to perform an automated hydropower assessment.

The automated hydropower assessment procedure is detailed in Chapter 6 for both run-of-river and impoundment schemes. A model of a typical run-of-river hydro scheme is implemented based upon the RETScreen method for yield estimation. The influence of penstock friction is accounted for by solving the Colbrook equation for variable flowrates given penstock material roughness. A financial model of scheme components is developed that combines some of the

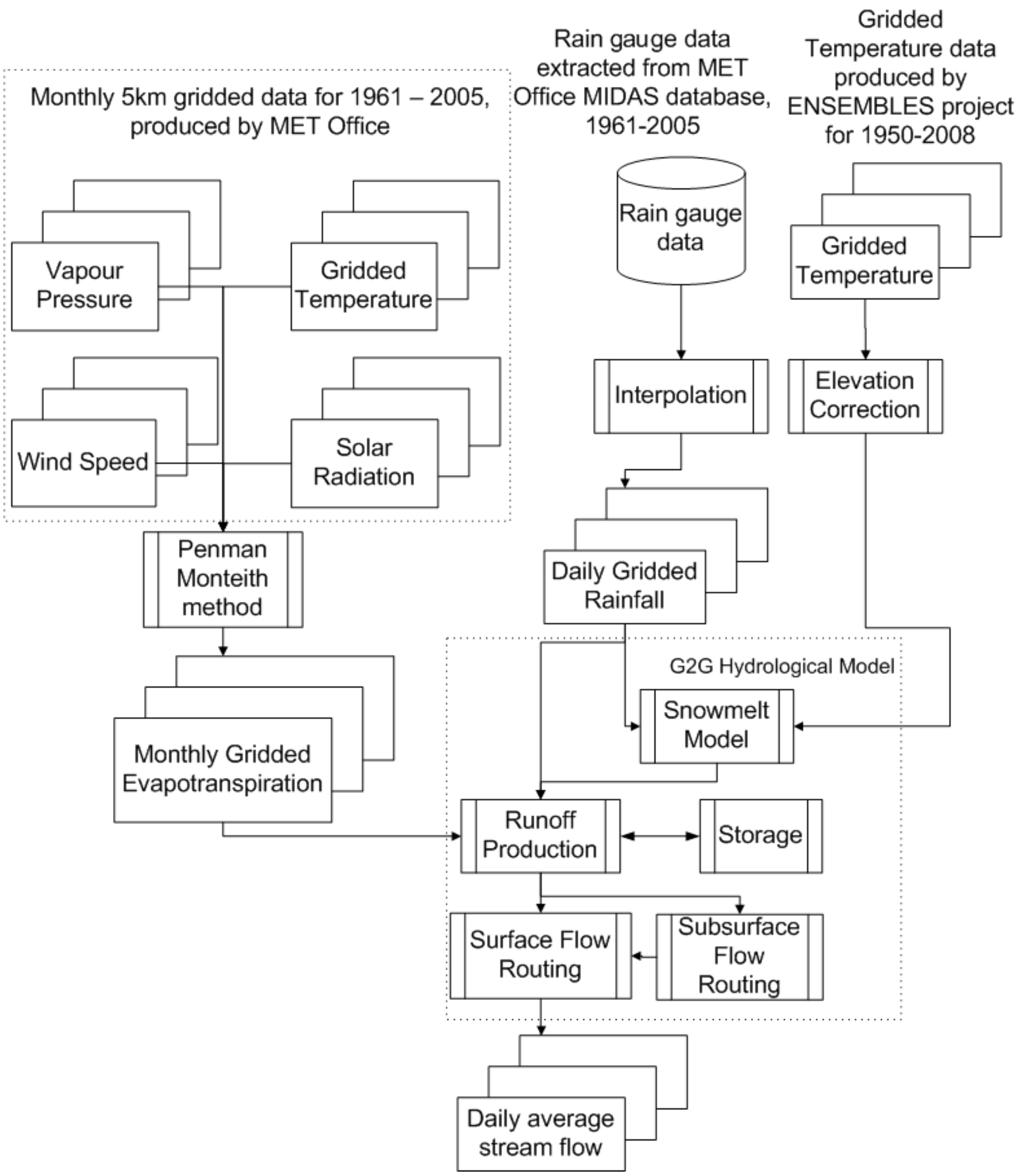

Figure 2.13: Diagram of hydrological modelling approach

RETScreen approach with other information for the UK. This allows trials of different scheme layouts and designs to be made at points along the river network, allowing optimisation of penstock length and diameter and turbine size. A schematic for the assessment algorithm is given in Figure 2.14. The search algorithm is enhanced by its ability to incorporate impoundments to allow over-sized schemes to be deployed taking advantage of operation during peak demand hours with high electricity sales prices. A dam search algorithm is used to find suitable locations for dams and allows an estimation of resulting impoundment volume based upon the dam dimensions and the local geography. A simple reservoir model is used together with time series flow data to allow an assessment of the typical operating characteristics and yield of impoundment based sites.

To assess the impact of climate change upon the Scottish hydropower resource time series data for evapotranspiration and rainfall are produced using the UKCP09 weather generator for 4 sample catchments. A hypothetical run-of-river scheme is placed in each of the catchments and a comparison is made of yield and capacity factor under a baseline climate and a future climate. This assessment is included with the results of the hydropower assessment in Chapter 7.

2.14 Chapter Summary

This chapter provides a lengthy introduction to the key technical aspects necessary to underpin the development of a sophisticated new hydropower assessment for Scotland. It is by no means an exhaustive summary of all known information on each relevant topic, rather an effort to demonstrate wide appreciation of the prior art in hydrological modelling, hydropower engineering and other issues. These factors are elaborated on in the relevant chapters that follow.

Figure 2.14: Overview of hydropower search model

3
Development of Gridded Meteorological Datasets

"Climate is what we expect, weather is what we get."

– Mark Twain

3.1 Chapter Summary

Older lumped hydrological models such as the Stanford Watershed Model, developed to run with limited computational resources, would typically use lumped parameters and meteorological data to represent catchment processes. The growth of GIS, developments in the fields of climate and meteorological modelling and availability of low cost computing have led to increased use and availability of gridded data. This data has numerous advantages over traditional point source records, most importantly data consistency and portability. This is particularly noticeable in the field of atmospheric modelling where the development of standardised grid sizes and formats, such as NetCDF, make it easy for data to be archived and accessed by researchers, and coupled with different models. Data quality is less transparent than traditional point measurements as gridding and interpolation procedures will introduce additional sources of error. If not produced directly by a meteorological or climate model, gridded data is produced from station measurements; this is readily performed for rainfall and temperature variables. Evapotranspiration estimates have also been produced in a gridded format for some time in the UK by the MORECS system operated by UKMO (Hough and Jones, 1997).

To enable long term hydrological simulation of the Scottish river network, daily gridded 1 km by 1 km rainfall time series have been created for the period 1961-2005 using daily UKMO rain gauge data and a thin plate spline interpolation method. Monthly 5 km by 5 km gridded potential evapotranspiration (PET) has been calculated using monthly grids of meteorological variables developed by Perry and Hollis (2005) as part of the UKCP09 project for 1961-2005.

A 1 km by 1 km gridded daily temperature dataset for 1961-2005 has been created by applying a simple downscaling technique to a 0.25 ° by 0.25 ° European temperature dataset created as part of the ENSEMBLES project (Haylock et al., 2008). The creation of these datasets is explained in this chapter.

3.2 Rainfall

3.2.1 Introduction

Traditionally single rain gauge stations within a catchment have been used to provide data to a hydrological model. With larger catchments it is common to use multiple local rain gauges, with nearest neighbour techniques such as Thiesien polygons used to combine the data from the gauges and determine rainfall between them. There can be problems with missing data or short record length when trying to perform long-term hydrological modelling over multiple years. Gauge networks are usually sparse in rural upland areas with low population density due to to the difficulty and cost of maintaining gauges in remote locations. In an attempt to overcome these issues and produce a consistent dataset with universal geographic coverage it is common to grid observed meteorological data. Numerous interpolation and geostatistical techniques have been applied in the literature to allow development of such a datasets. Difficulties are encountered in areas of sparse gauges and complex terrain due to the spatially heterogeneous nature of rainfall, shadowing effects of terrain and interaction with other meteorological variables. As such, rainfall patterns can be very localised with relatively close areas receiving significantly different amounts of rainfall in a single day. Attempts to improve the accuracy of rainfall interpolation have led to the use of statistical interpolation techniques such as Kriging (Goovaerts, 2000; Haylock et al., 2008; Jeffrey et al., 2001) and thin plate splines (Tait et al., 2006) which can incorporate independent variables such as elevation or the long term average rainfall. Johansson and Chen (2003) developed regression equations linking rainfall intensity to other geographic and meteorological variables such wind speed and direction, elevation, roughness of terrain, distance from coast.

3.2.2 Data

The complete UKMO land surface observations database (MIDAS) is available from the British Atmospheric Data Centre (UKMO,2012a) as a series of coma delimited ASCII files. For daily rain gauge data each record contains a measurement made on a particular day at a specific weather station. Each station has a unique identifier code and a time stamp detailing the actual observation time is added to each to each record. An example of the data format is shown in Table 3.1. The geographic position of each weather station in the UK is provided by the Met Office in an Excel spreadsheet as longitude and latitude.

PK	Attribute	Description / Units / Precision
*	id	rain gauge number
*	id_type	Identifier type
*	ob_date	Date of observation
*	version_num	Use the row with '1', as this has been quality checked by the Met Office
*	met_domain_name	Message type
	ob_end_ctime	Clock-time at end of observation
	ob_day_cnt	Observation day count
	src_id	Unique source identifieror station site number
	rec_st_ind	State indicator for the record**
	prcp_amt	Precipitation amount Units=1mm, reported to the nearest 0.1 mm
	ob_day_cnt_q	QC code - day count**
	prcp_amt_q	QC code - precipitation amount**
	meto_stmp_time	Met Office receipt stamp time
	midas_stmp_etime	Elapsed time to storage in MIDAS minutes
	prcp_amt_j	Descriptor - precipitation amount**

Table 3.1: Rain gauge data format

There are significant gaps in the UKMO rain gauge record. Even well established stations have significant numbers of omissions due to problems with gauges or unavailable personnel. It quickly becomes apparent that to use the extensive record in a meaningful way would require significant infilling either in time, space or both. This makes daily rainfall surfaces attractive as a tool to make up for shortfalls in the consistency of available gauge data and provide a means of making predictions at points between gauges.

Rainfall radar data is available for the whole UK at 5 and 15 minute temporal resolution and 1 km spatial resolution; this is referred to as NIMROD (UKMO, 2012b). Radar can be considered a highly sophisticated form of spatial interpolation, the radar returns are weighted according to gauge measurements to produce a rainfall surface for each time interval. As the data is only available from late 2002 it was not used as this would not enable the creation of a consistent long-term rainfall dataset.

The Standard Average Annual Rainfall (SAAR) dataset is a 1 km rainfall climatology for 1961-1990 standard period. It is held by CEH Wallingford and is based upon UKMO data. It is unclear how this dataset was created, however it was likely developed from early earlier UKMO isoheytal maps using "expert knowledge" to make it consistent with river gauge readings and catchment water balances.

3.2.3 Interpolation Methods

Three interpolation approaches have been considered: Inverse Distance Weighted (IDW) interpolation, Thin Plate Spline (TPS) and Kriging, each are briefly discussed based upon descriptions by Vieux (2004).

IDW is a simple method to implement and was used by UKMO to interpolate a range of variables, including rainfall, to produce monthly and daily datasets (Perry and Hollis, 2005; Perry et al., 2009). IDW tends to over-fit the resulting surface at observed points leading to a characteristic tent pole effect, where local minima or maxima are found at the points of observation. This causes outliers in the observed data to have a large impact upon the interpolated surface. It is not possible to include additional independent variables using basic IDW therefore it is expected that the UKMO daily rainfall dataset will contain a degree of bias due to poor gauge density in upland catchments.

Kriging is a complex stochastic method which was developed for mining applications and has been used to incorporate elevation into the spatial interpolation of rainfall (Goovaerts, 2000). Kriging is described as an optimal spatial estimation method and relies upon a statistical model of the variance of the quantity being interpolated as it varies with distance (and optionally additional independent variables) using what is known as a semivariogram. This is similar to fitting a probability density function to the sample data. Once this has been created a surface is created by weighting observed values according to the separation distance. Kriging is a complex method to implement, involving the *a priori* setting of various, somewhat arbitrary, parameters and the choice of a suitable stochastic model. This requires a large degree of skill and experience.

TPS is a deterministic interpolation method based upon the analogy of bending a thin steel plate to fit spatial data. TPS allows the creation of surfaces similar to those provided by Kriging without the difficulty of having to fit a semivariogram to the data (Hutchinson, 1994, 1998, 1995; Jeffrey et al., 2001; Ruelland et al., 2008). TPS methods use the assumption that the surface function should pass as closely to the points of observation while retaining a degree of smoothness. This data smoothing characteristic is useful when dealing with noisy rain gauge data subject to measurement error and data quality issues.

A Thin Plate Spline (TPS) method has been adopted as it has been shown to provide similar performance to Kriging while avoiding much of the complexity associated with that method. The smoothing properties minimise the impact of outliers on the resulting surface and it is possible to incorporate independent variables into the interpolation. The *fields* package developed by The National Centre for Atmospheric Research (NCAR) (based upon the previous FUNFITS package) implements a number of geostatisical methods using the R statistical language including a TPS function which has been used in this work (Fields Development Team, 2006).

3.2.4 A Closer Look at Thin Plate Splines

The thin plate spline is the spatial analogue of the cubic spline. Given a set of data points on a Cartesian grid a weighted combination of thin plate splines centred around each point gives the interpolation function that passes closest to the points (minimising the sum of square residuals) while minimising the “bending energy”, or in other words maintaining a minimum level of smoothness. The surface roughness value is calculated based upon the derivatives of the highest order polynomials of the spline function (Hutchinson, 1994).

Given n data values $y(x_i)$ at locations x_i a function $f(x_i)$ is developed to fit the data points while maintaining a minimum level of smoothness. To achieve this interpolation surface is formed from function $f(x_i)$ which minimizes:

$$\sum_{i=1}^{n}(y(x_i) - f(x_i))^2 + \lambda J_m(f) \tag{3.1}$$

where $J_m(f)$ is a surface roughness penalty, λ controls the trade-off between size of residual fit and smoothness. This assumes that λ is already known. When λ is unknown it is typically estimated using a Generalized Cross Validation (GCV) method (Utreras, 1987).

Cross Validation is a method of calculating the spline function’s predictive error by removing each point observation in turn and summing the absolute residuals measured at the omitted point based upon a model fitted to all other data points. The *fields* GCV method incorporates the model residual fit with the model roughness to produce a cost for a given λ value. The roughness is estimated by calculating the effective number of parameters used within the TPS function, a measure of the order of polynomials used. By trading off the residual fit with model smoothness regularisation is applied to the data, preventing over-fitting and reducing the impact of outliers on the resulting surface. The GCV procedure has the added advantage of providing a robust estimate of the RMSE of the fitted surface (Fields Development Team, 2006).

Incorporation of an additional independent variable is achieved using a fixed part of the model. A coefficient θ is produced relating the independent variable $Z(x)$ to the fitted spline surface such that:

$$f_{total}(x) = \theta \times Z(x) + f_{spline}(x) \tag{3.2}$$

3.2.5 Processing and Interpolation Procedure

A database was created to join the geographic data with the raw weather station data. Once joined, the data were processed into files containing all the rainfall observations for a single day, each record contained the rain gauge value, the SAAR value at the site of the gauge and the Northing and Easting. The files were saved for each individual day and formed the input to the interpolation procedure (see Figure 3.1).

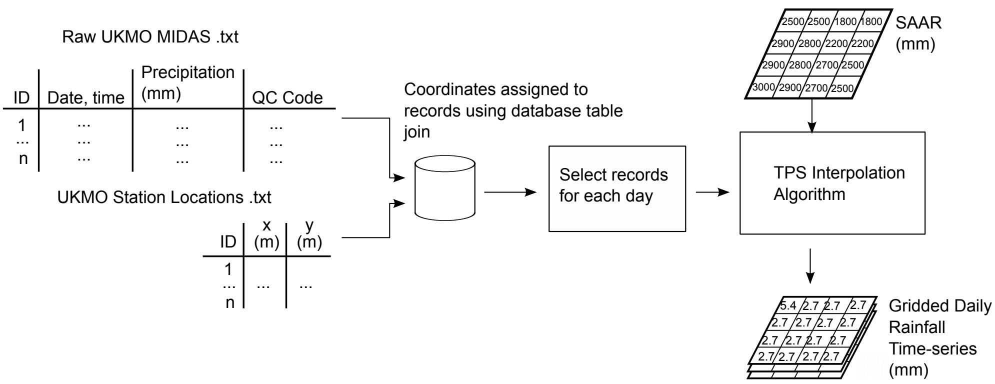

Figure 3.1: Illustration of Rainfall Gridding Procedure

To account for orographic effects the SAAR dataset (see Figure 3.2) was used to weight the interpolation surface, based upon the approach used by Tait et al. (2006) who found the use of a rainfall climatology as independent variable produced better estimates of rainfall at high elevations. Using the SAAR dataset to correct the surface for high elevation catchments affected by orographic enhancement should minimise bias due to poor geographic distribution of rain gauges. This should enable greater hydrological model accuracy than would be possible using the UKMO daily 5 km gridded rainfall which only uses a simple IDW approach (Perry et al., 2009).

After geographical coordinates were added to the raw gauge data the *fields* implementation of the TPS procedure was used to perform gridding. The point gauge data was interpolated onto a 1 km Cartesian grid on the British National Grid coordinate system.

The *fields* package represents the observations on a relatively coarse grid, to allow the aggregation of spatially close observations. This forms part of the GCV procedure whereby regions are removed rather than individual observations. If individual stations are removed during GCV then calculated RMSE is overly optimistic as there is typically little error between very close stations. Fig. 3.3 shows data for the 2nd of January 1990, a day with light rainfall across the country and regions of more heavy rainfall. A value of 15 mm has been recorded in the North-West Highlands that is much greater than surrounding values, the regularisation applied by the TPS function should reduce the impact of this outlier on the resulting surface.

3.2.6 Rainfall Climate as an Independent Variable

The surface is calculated based upon observations and the SAAR values at the points of observation. This produces a surface that is effectively a regression model fitted to the SAAR data. The final prediction surface is created by multiplying the SAAR grid by the regression coefficient and adding the prediction surface created for the SAAR grid (see Figure 3.4). This immediately makes the rainfall surface more geographically specific and increases the level of rainfall on the highest peaks. RMSE is slightly reduced, when this approach is used however given the lack of high elevation rain gauges the rainfall surfaces would dramatically under-predict catchment rainfall volumes.

The plots in Fig. 3.5 show a scatter of the residual fit, magnitude of RMSE to predicted value, the number of degrees of freedom chosen for the model through GCV selection of lambda and a histogram of the RMSE values by size. The GCV score can be seen to fall as the number of spline parameters is increased (increasing value of λ) as the RMSE of the model fit falls, the GCV reaches a minimum at approximately 180 parameters before the score starts to increase as model roughness outweighs improvements in the model fit. The 15 mm value clearly creates a large outlier in both the scatter plots. There are other outliers typically at greater rainfall values, and appearance of under-prediction.

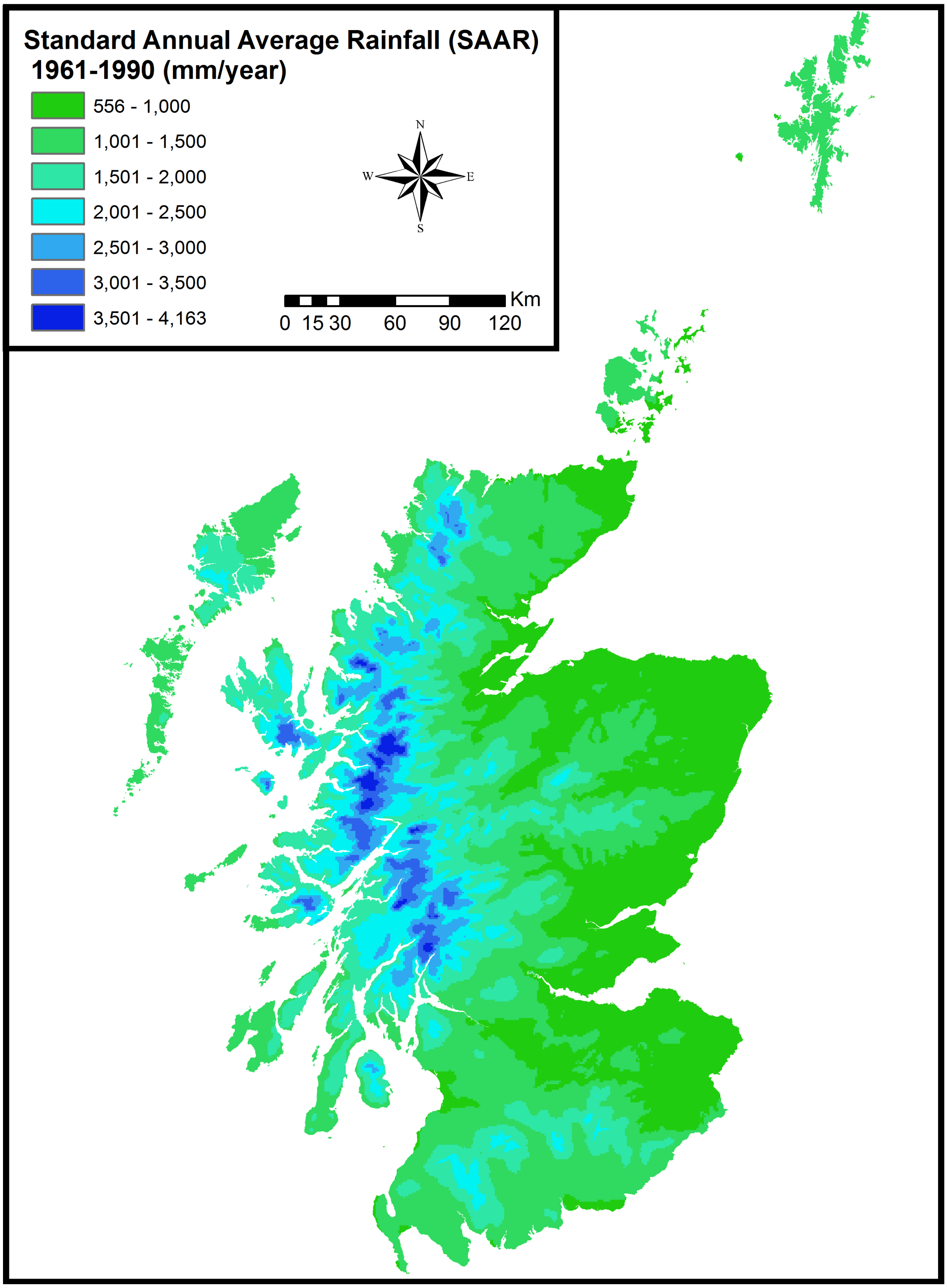

Figure 3.2: 1961-1990 Standard Average Annual Rainfall (mm)

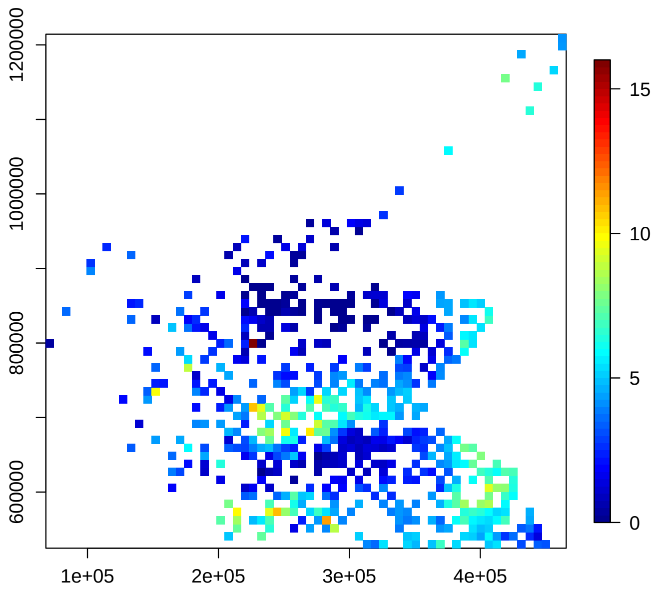

Figure 3.3: Rainfall data aggregated on coarse grid

3.2.7 Available Observations

The number of gauges reporting on each day varied across the period of study, the largest number of reported gauges occurred during the 1970s and 1980s, declining during the 1990s. The 1st of January 1961 had only 69 gauges available as shown in Figure 3.6; this number increased dramatically later in the year and remained above 370 for the remainder of the study. There are large clustering of gauges around habited areas, with the gauge network becoming much sparser in the Highland upland areas. This lack of gauges will lead to greater interpolation error at these remote locations. This is unfortunate as these areas have some of the highest annual rainfalls in the country, making it likely that any interpolation method will lead to significant underestimation of rainfall at the highest elevations.

3.2.8 Results

Processing was carried out using a number of Sun workstations and rainfall grids were produced for each day between 1961 and 2005. Example output grids are shown in Fig. 3.7 for the first few days of January 1990. The surfaces are reasonably smooth and the use of the SAAR dataset as an independent variable has provided a more detailed representation of the orography. The RMSE recorded for each day's fit was assessed to identify days with poor fit. Several days had a very poor fit with RMSE in excess of 40 mm. On closer inspection it was found that this was

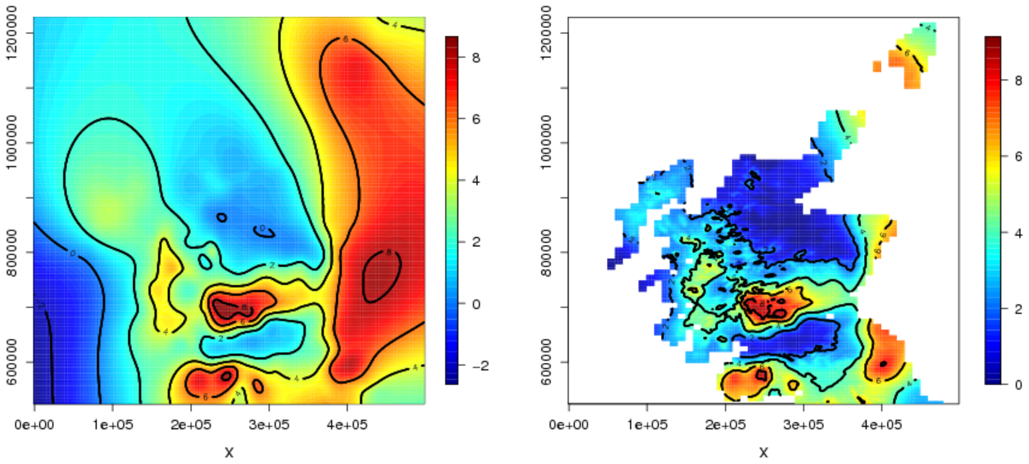

Figure 3.4: Interpolation without SAAR (left) and with SAAR (right)

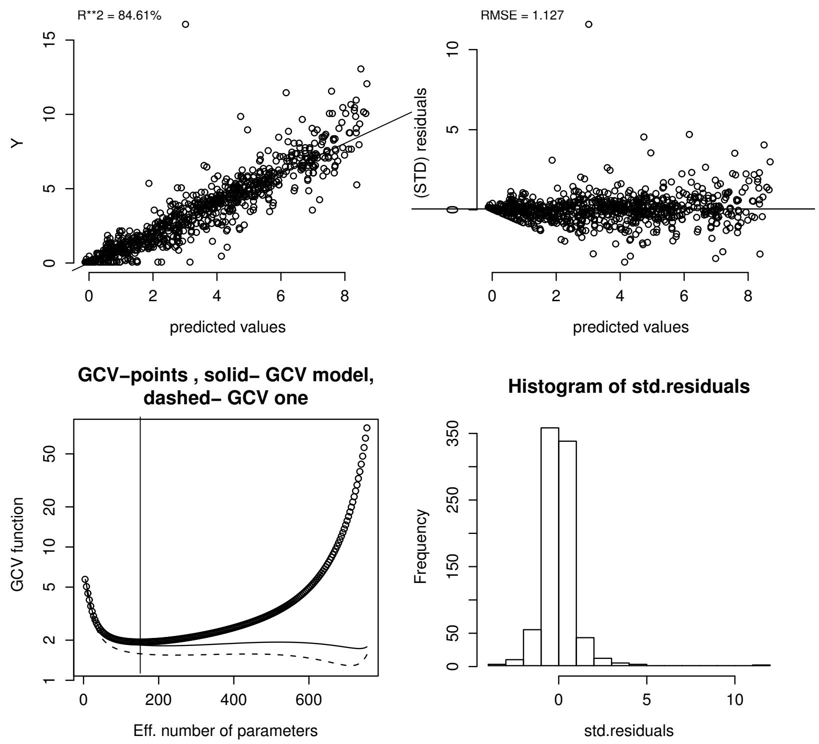

Figure 3.5: Various error statistics for 2nd Jan 1990

due to irregularly high gauge readings in a single location typically 150 mm or greater. These erroneous values were removed and the gridding procedure was repeated for these days.

Once clearly erroneous data was removed, it was found that the daily TPS fit RMSE remained below 7 mm. Days of higher rainfall tended to produce the highest RMSE values especially when there was a heavy downpour in a relatively localised area. Figure 3.8 shows RMSE

Figure 3.6: Available gauges on the 1st of Jan for 1961, 1971 (both top), 1981, 1991 (both middle) and 2001 (bottom)

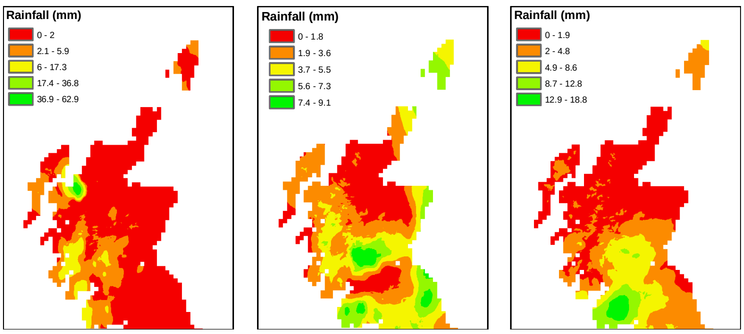

Figure 3.7: Example of typical gridded rainfall on 1st, 2nd and 3rd of Jan 1990

plotted as a rather noisy time-series, the 365 day average corresponds to the results published by Perry and Hollis (2005) and Tait et al. (2006) who respectively achieved average RMSE values of 1.3 mm and 1.2 mm. RMSE can be seen to increase after 1980, this is likely caused by the lower number of gauges reported from 1980 onwards. Figure 3.9 shows RMSE binned as a histogram: most days have error in the range 1-3 mm with the vast majority having below 4 mm of error. It should be noted that these errors represent the residuals measured at gauges that formed points in the interpolation process, while this is as useful indicator regarding the typical expected error on a given day it is important to also perform validation testing using gauges excluded from the process.

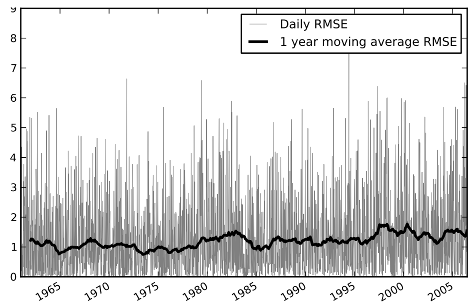

Figure 3.8: RMSE error for each day of 1961-2005 dataset, error values are typically lower than 7 mm, 365 day moving average corresponds with overall average of 1.2 mm RMSE

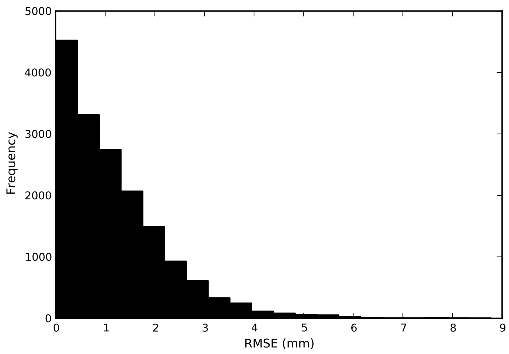

Figure 3.9: Histogram showing binned RMSE values for whole rainfall dataset, the vast majority of days have RMSE below 4 mm

3.2.8.1 Validation

To validate the procedure a number of gauges were omitted from the interpolation and their recorded values were compared to the resulting surfaces. Residuals were analysed and the RMSE was calculated for each gauge over the year 1990. The 8 gauges were selected as they have a geographical dispersion and a full record for 1990. The locations of all gauges and the 8 excluded are shown in Figure 3.10. Time series and scatter plots of gauge recordings compared to the interpolated values are shown in Fig. 3.11.

The fit is generally good. Higher residuals can be seen at higher rainfall intensities, as would be expected. The gauge at Cassley, Sutherland is the most remote of the omitted gauges, located at the bottom of a steep slope surrounded by complex terrain. This gauge experiences the greatest error, significantly underestimating the annual rainfall at that site by 30%.

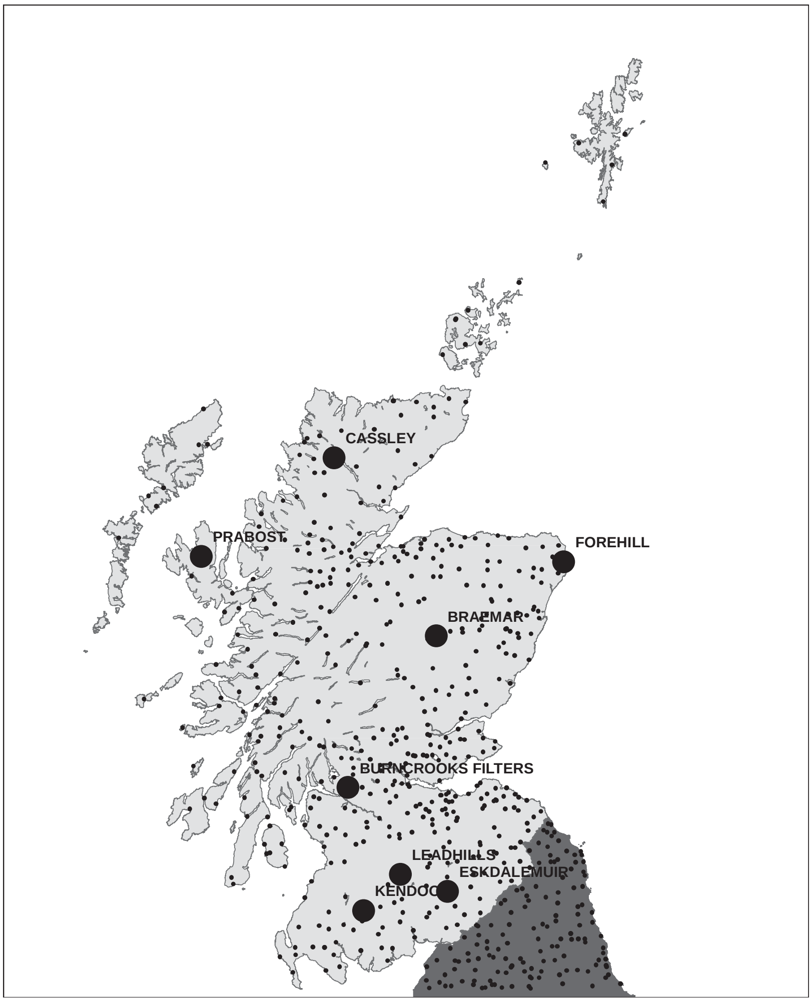

Figure 3.10: Locations of all rain gauges and the 8 specifically excluded

3.2.9 Discussion

The resulting dataset has been shown to be of good quality and greatly simplifies the task of forcing a distributed hydrological model compared to using point weather station data of varying spatial and temporal quality.

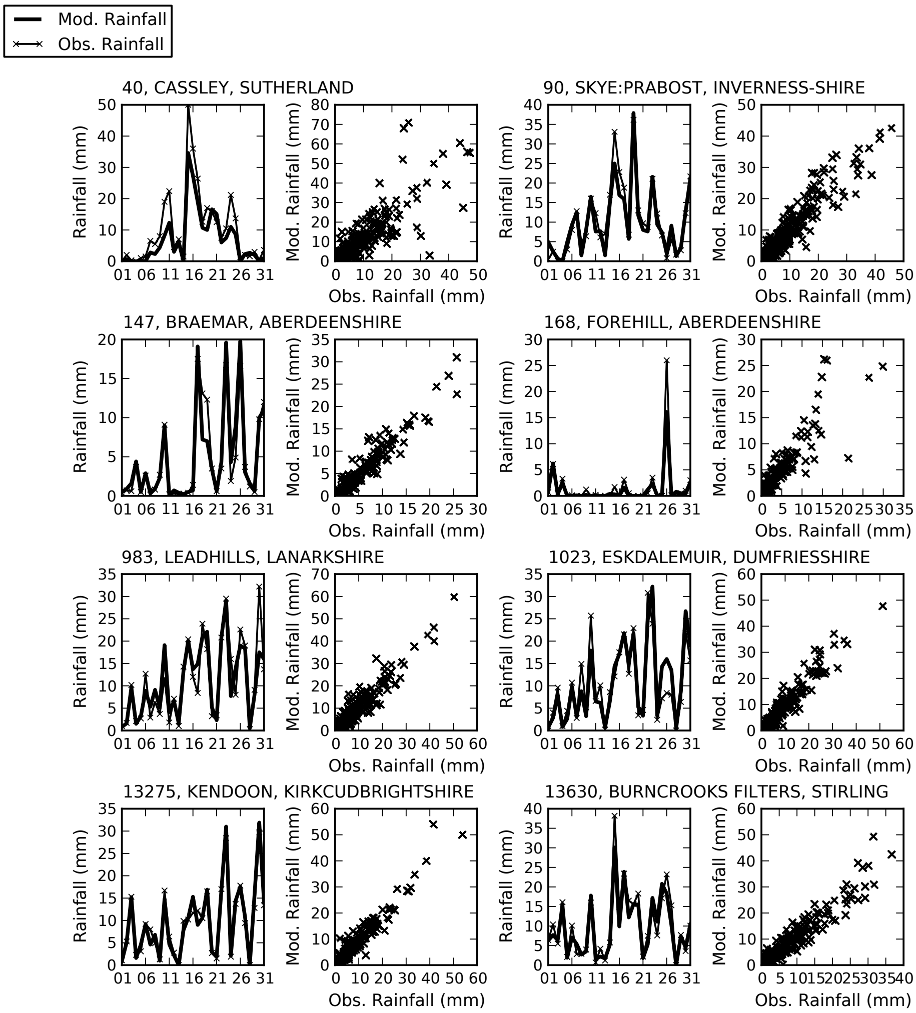

Figure 3.11: 8 gauges excluded from interpolation over year 1990. Left hand time series plots for days of Jan 1990, scatter plots show observed versus modelled for whole of 1990

3.3 Evapotranspiration

3.3.1 Introduction

Evapotranspiration (ET) is defined as the use of water by vegetation for transpiration and evaporation from the land surface due mainly to solar radiation. Potential evapotranspiration (PET) is the amount of evapotranspiration that would occur if there are no limitations to available moisture. Numerous methods exist for calculating PET mostly using empirically formulae. The most physically realistic method is that developed by Penman and then further refined by Monteith. The Penman-Monteith equation requires daily mean temperature, wind speed, relative humidity, and solar radiation to predict net PET. The equation is based on the idea that different vegetation surfaces will have different fluxes of water consumption based upon conductance of the particular vegetation type. Future changes in PET could potentially have a large impact on Scotland's hydrology. The current temperate humid climate leads to catchments having sufficient soil moisture to enable evapotranspiration processes most of the time. A future climate with longer dry spells, would be expected to limit available soil moisture causing AET to become more critical than than PET, with consequent impact on flow regime.

3.3.2 Data

The 5 km monthly Met Office datasets were used to produce ET values on the same grid. As solar radiation is not measured at many stations in the UK this is not available as part of the Met Office gridded data. Sunshine hours is available however, therefore a conversion from sunshine hours to solar radiation based upon a method developed by Suehrcke (2000) based upon the Prescott-Armstrong equation was used and is discussed in a later section (See Figure 3.12). A sample of MORECS data was available for two MORECS squares located in the West Highlands, these were used to validate the ET grids. Data from a lysimeter study carried out near Balquihidder were used for validation (Wright and Harding, 1993). Gauged streamflow for a number of catchments with associated catchment average rainfall were used to assess the ability to close the water balance.

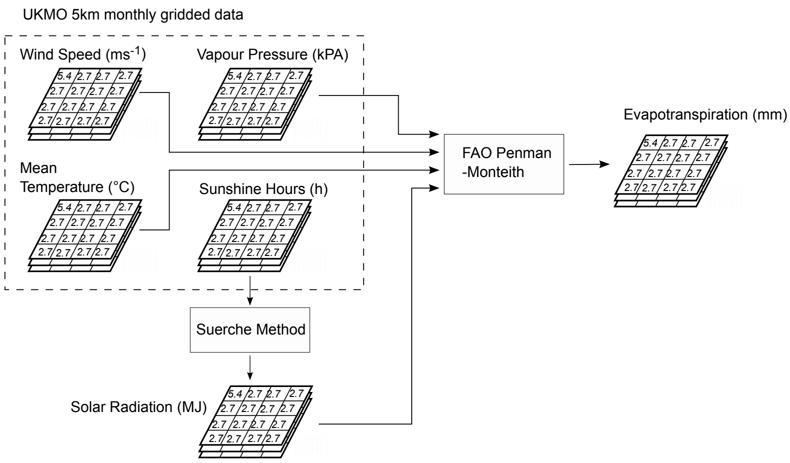

Figure 3.12: Illustration of PET gridding procedure using FAO 56 Penman-Monteith method

3.3.3 FAO 56 Penman Monteith

The FAO 56 Penman-Monteith method developed by Allen (1998) is recommended by the UN FAO for the estimation of PET for agricultural purposes and provides a method based upon the Penman-Monteith equation using several simplifying assumptions and the concept of a reference crop (Monteith, 1965). Although the most physically realistic method available, the data requirements of the Penman-Monteith equation are much greater than the simpler equations such as Thornthwaite. At its most complex the equation can be driven with sub-daily weather station data and time varying vegetation data. This is of course very useful for real time control of an irrigation system. However, to develop a usable ET dataset at a national scale certain compromises have to be made. The use of monthly average meteorological data to produce a monthly ET estimate greatly reduces the complexity of the problem. However daily and sub-daily phenomenon including diurnal effects or out of season short hot and cold spells will be not be considered. While a daily PET dataset is desirable the data required to develop one on a national scale is simply not available. Development of daily grids for solar radiation, wind speed and vapour pressure from observation data would be a significant task better suited to numerical weather forecast models.

Table 3.2 gives an indication of typical evapotranspiration rates in mm/month for different climatic regions. Values for Scotland would be expected to lie in the temperate humid and sub-humid range, with the values at 10 ° C representing winter months and values at 20 ° C representing typical summer months.

Average ET for different agroclimatic regions in mm/day			
Regions	**Mean daily temperature** (°C)		
	Cool ~10 °C	**Moderate** 20 °C	**Warm** > 30 °C
Tropics and subtropics			
- humid and sub-humid	60 - 90	90 - 150	150 - 210
- arid and semi-arid	60 - 120	120 - 180	180 - 240
Temperate region			
- humid and sub-humid	30 - 60	60 - 120	120 - 210
- arid and semi-arid	30 - 90	120 - 210	180 - 270

Table 3.2: Typical daily ET values for different climates; values for Scotland would be expected to lie in the temperate humid/sub-humid range

The implementation of the FAO 56 method relies upon the use of a reference crop of grass defined as: "A hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23."

PET rates for particular crops or vegetation can then be calculated using a seasonally varying crop coefficient which which is applied to the reference PET rate. In this application of the FAO 56 method PET was calculated based solely upon a reference grass surface. Ideally land-use data would have been used to develop crop coefficients based upon typical Scottish growing seasons, however, a significant level of effort and expertise would be required to add this additional complexity.

The Penman-Monteith equation for evapotranspiration is:

$$PET = \frac{\Delta(R_n - G) + \rho_a c_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)} \tag{3.3}$$

where:
R_n is the net radiation (MJ m^2 day^{-1})
G is the soil heat flux (MJ m^2 day^{-1})
$(e_s - e_a)$ represents the vapour pressure deficit of the air (kPa)
ρ_a is the mean air density at constant pressure (kg m^{-3})
c_p is the specific heat of the air (MJ kg^{-1} $^\circ$ C^{-1})
Δ represents the slope of the saturation vapour pressure temperature relationship (kPa $^\circ$ C^{-1})
γ is the psychrometric constant (kPa $^\circ$ C^{-1})
r_s is the bulk surface resistance (s m^{-1})
r_a is the aerodynamic resistance (s m^{-1}).

The use of the reference surface negates the requirement to calculate the surface resistance as this is already defined, based upon assumed crop height of 0.12 m and wind speed and humidity measurements made at at 2 m, giving:

$$r_a = \frac{208}{u_2} \tag{3.4}$$

where u_2 is the wind speed (m s^{-1}) at 2 m. The bulk surface resistance r_s is a measure of the resistance of vapour flow through the crop and soil surface. This varies depending upon how much the crop covers the soil surface. The following equation is used to approximate this effect:

$$r_s = \frac{r_l}{LAI_{active}} \tag{3.5}$$

where r_l is bulk stomatal resistance of the well-illuminated leaf, the Leaf Area Index (LAI) is used to represent the area of leaf coverage for a given area of soil. The grass reference surface is assumed to have an LAI_{active} of 1.44. The bulk stomatal resistance r_s is the average resistance of a leaf and is assigned a value of 100 s m^{-1}. This gives a surface resistance (r_s) of 70 s m^{-1}.

Given these assumptions the FAO Penman-Monteith equation for a reference grass surface can be defined as follows:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{3.6}$$

3.3.4 Solar Radiation

One of the major data requirements of the Penman-Monteith equation is solar radiation. This is not widely measured in the UK, however the measurement of sunshine hours is much more common. This is reflected in the available 5 km UKMO gridded datasets which includes monthly average sunshine hours.

To develop grids of solar radiation values, available interpolated grids of sunshine duration measured by Stoke sunshine recorders were converted to grids of Solar radiation. The Prescott-Armstrong equation is commonly used for this purpose. Relating average daily extraterrestrial radiation $\bar{H}_o$ to the monthly average daily horizontal surface radiation $\bar{H}$ the equation is defined:

$$\frac{\bar{H}}{\bar{H}_o} = a + bS \tag{3.7}$$

where a and b are empirical constants and S is the monthly average recorded time fraction of bright sunlight. Although widely applied, a disadvantage of this approach is that a and b have to be calibrated based upon local solar radiation measurements making application of the equation regionally problematic.

To overcome this Suehrcke (2000) developed a modified method that allows regional calibration to be performed based upon the following relationship:

$$f_{clear} = \left(\frac{\bar{K}}{\bar{K}_{clear}}\right)^2 = \frac{N_{sun}}{N_{pot}} \tag{3.8}$$

where f_{clear} is the time fraction that no significant clouds block the sun; this can be considered equivalent to the ratio of number of sunshine hours recorded in a month N_{sun} to potential sunshine hours in a month N_{pot}. $\bar{K}$ is the monthly average daily clearness index and $\bar{K}_{clear}$ is the monthly average clear sky clearness index, a measure of how clear the sky is when direct sunshine is being recorded. This is a parameter calibrated for the region and was found to be 0.74 for Scotland.

$\bar{K}$ is the ratio of monthly average daily horizontal radiation $\bar{H}$ [J m^{-2}] , to the monthly average of daily horizontal surface extraterrestrial radiation $\bar{H_o}$ [J m^{-2}], calculated based upon the solar constant of 1.366 kW m^{-2} and the average day length and declination for a given month of the year.

$$\bar{K} = \frac{\bar{H}}{\bar{H_o}} \tag{3.9}$$

By rearranging equation 3.9 and substituting equation 3.10 the formula for monthly average daily horizontal radiation $\bar{H}$, can be calculated based upon extraterrestrial radiation $\bar{H_o}$ the monthly average clear sky clearness index $\bar{K}_{clear}$, the number of sunshine hours in a month and the potential sunshine hours in a month.

$$\bar{H} = \sqrt{\frac{N_{sun}}{N_{pot}}}\bar{K}_{clear}\bar{H_o} \tag{3.10}$$

3.3.5 Solar Radiation Validation

Once the monthly solar radiation grids were calculated a comparison was made with solar radiation values directly measured at 4 UKMO stations located across Scotland (see Figure 3.13). The results of this comparison are shown in Figure 3.14. There is a good fit between the monthly observed solar radiation values and those calculated using the Suehrcke modified Angstrom-Prescott method.

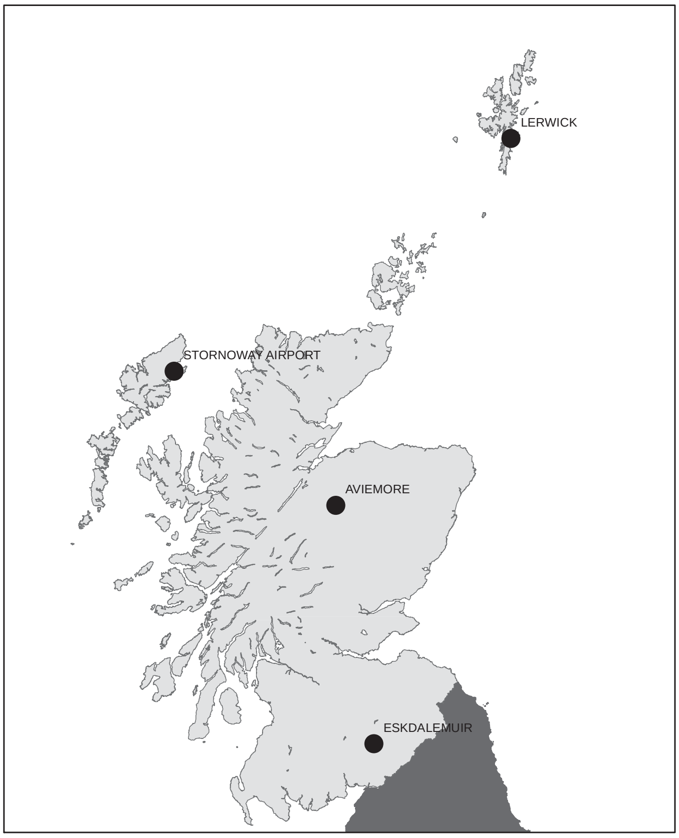

Figure 3.13: Met stations selected to validate solar radiation grids

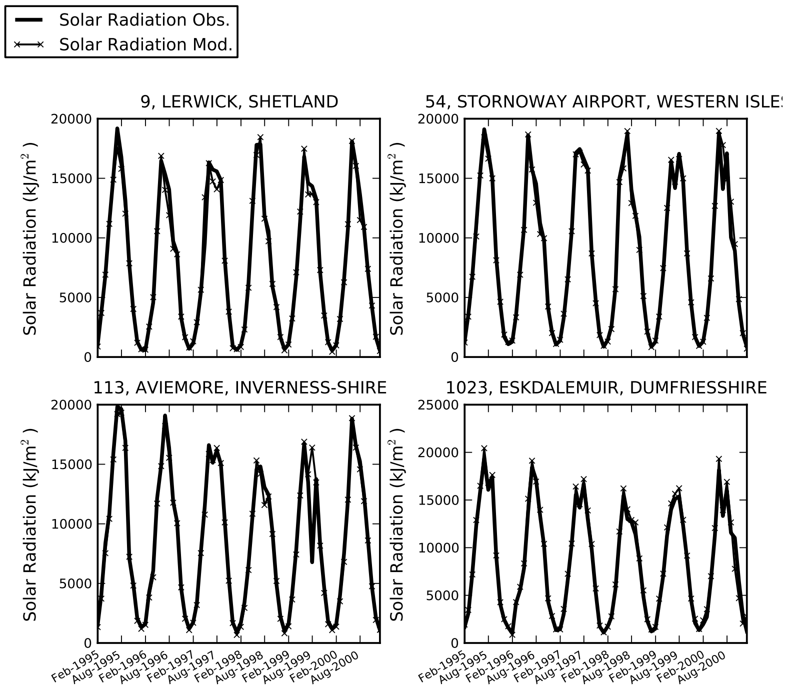

Figure 3.14: Comparison of modelled and observed solar radiation data

3.3.6 Results and Validation

Grids of monthly ET values were calculated for 1961 to 2005 using Equation (3.6) using the UKMO 5 km gridded datasets for mean temperature, wind speed, vapour pressure and the solar radiation grids detailed in the previous section.

Validation was carried out using three methods. Ideally the results would be compared to those measured by lysimeters with long term time series located at points around the country. However this data is not readily available, therefore only a simple comparison has been made with a limited amount of lysimeter data. UKMO MORECS data was available for two 40 km grid squares located in the West Highlands between Loch Fyne and Loch Lomond. This has been used to perform a comparison with another Penman-Monteith PET estimate. A final check was performed by calculating the average annual PET over the 30 year period 1961-1990 and using this to calculate catchment water balances.

3.3.6.1 Lysimeter Data

As part of a hydrological study carried out near near Balquihdder in Perthshire Wright and Harding (1993) installed two lysimeters and a weather station in an upland highland catchment. The readings from the lysimeters were logged from April to October 1988. In addition, a Penman-Monteith estimate of PET was made using data from the weather station. A time series plot of the 4 PET series (see Fig. 3.15) shows a reasonable fit with data from lysimeters A and B. The FAO 56 PET estimate is for PET and therefore would be expected to be higher than the lysimeter values especially for summer months where lack of soil moisture constrains actual evapotranspiration (AET). The plot of the site Penman estimate is consistent with this, showing a high value of PET for June compared to the lysimeter measured AET.

3.3.6.2 MORECS Data

UKMO MORECS data was obtained for reference squares 47 and 48 near Loch Fyne. A comparison was made with the gridded FAO 56 PET by averaging the 5 km PET grid cell estimates beneath the MORECS squares. While there is a good fit between the two estimates the FA0 56 data tends to be lower during winter months and peak summer months (see Figures 3.16 and 3.17). There are numerous potential explanations for these differences: e.g MORECS explicitly accounts for different land surface types and the seasonal change of leaf area index;

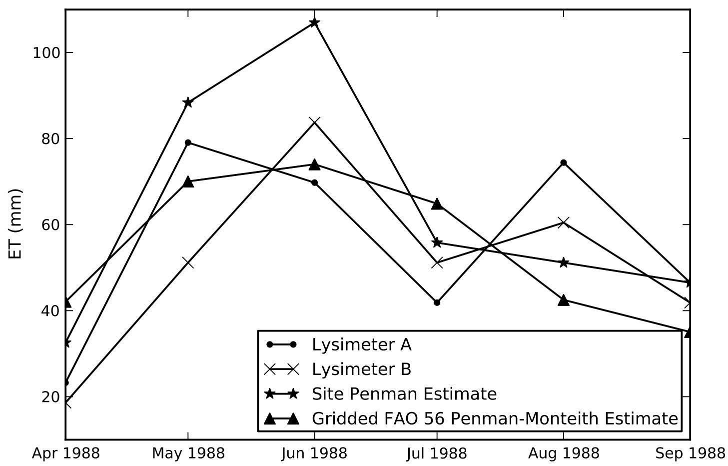

Figure 3.15: Results from a lysimiter study carried out in an upland catchment near Balquihidder. Local Penman ET estimates were produced from a catchment weather station

differences in the interpolation procedure; MORECS also applies a lapse rate to inland vapour pressure and temperature to normalise all values as a sea level equivalent.

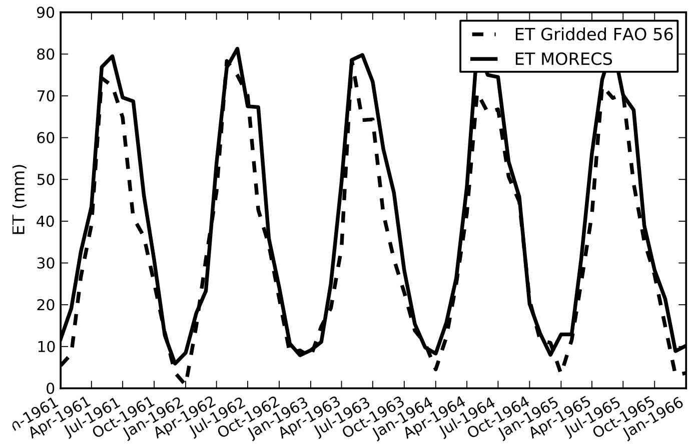

Figure 3.16: Comparison of FAO 56 gridded PET with MORECS PET for MORECS squares 47 and 48

3.3.7 Discussion

A monthly dataset of PET at 5 km resolution has been created and showed good performance. Although ideally daily time series would be used, it is extremely difficult to obtain the required data to achieve this temporal resolution on a national scale.

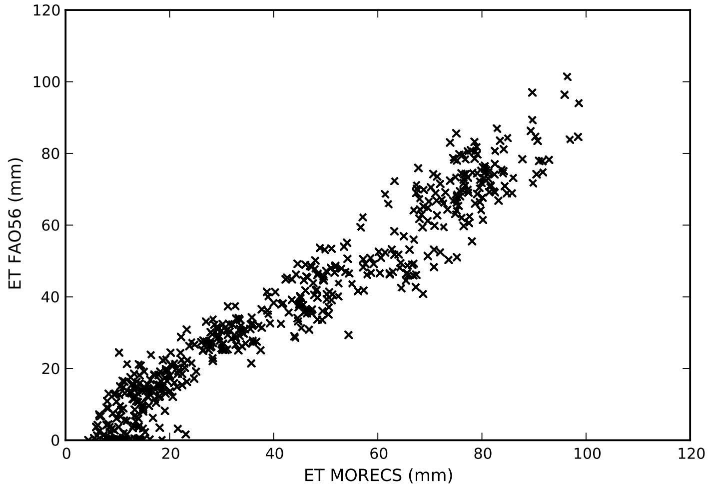

Figure 3.17: Comparison of FAO 56 gridded PET with MORECS PET for MORECS squares 47 and 48

3.4 Temperature

3.4.1 Introduction

To enable the representation of snowfall and snowmelt it was necessary to use gridded temperature data. A dataset of 0.25 by 0.25 deg (approx 25 km by 25 km) gridded daily surface temperature covering Europe for the period 1950-2006 has been developed as part of the ENSEMBLES project (Haylock et al., 2008). During 2010 a MET Office 5 km daily interpolated temperature time series was released. Had this dataset been released earlier it would have been used instead. At the time, however, the ENSEMBLES data represented the most complete and highest resolution temperature data available. The levels of snowfall in Scotland vary dramatically with elevation due to the decrease of temperature with increased elevation. Given a catchment with a wide range of elevation, for example the Spey, significant snowfall will only accumulate on the upland proportion. To allow suitable modelling it is necessary to resolve to a finer resolution than 25 km therefore it was deemed necessary to downscale the 25 km data to a 1 km grid.

3.4.1.1 Gridded Temperature Data

Haylock et al. (2008), interpolated temperature from 2316 (the exact number varies over time) European weather stations (see Figure 3.18). Significant efforts were made to remove erroneous readings from the raw data by identifying clearly incorrect values, (e.g. greater than 60 ° C) and by identifying and removing outliers. A three step interpolation procedure was used to account for the spatial trend between different European climatic regions. This allowed for greater interpolation error in areas with greater values. Firstly mean monthly temperatures were interpolated using thin plate splines on a 0.1 ° by 0.1 ° grid to describe the underlying spatial trend. Daily anomalies between station readings and the monthly average were then gridded using Kriging, and the interpolated anomalies were then applied to the monthly mean to produce the final dataset. A great advantage of kriging is that it allows the production of uncertainty estimates associated with the interpolation. This was used to create an estimate of standard error for every grid point on each day. The regional annual average standard error for mean temperature was found to lie between 0.6 - 0.76 ° C for the period 1950 to 2006. The level of standard error was found to be highly dependant upon the number of observations available.

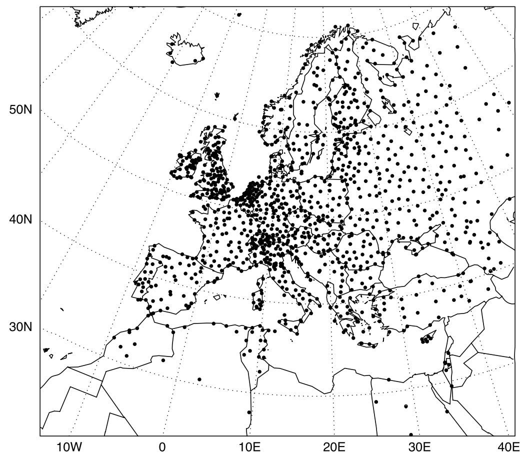

Figure 3.18: Stations used to interpolate temperature

3.4.2 Re-projection and Elevation Correction

The original ENSEMBLES dataset was provided as a 0.25 by 0.25 ° NETCDF dataset. It was necessary to project this data to British National Grid; this was achieved using the GDAL toolset (Warmerdam, 2008). It was found that there was some error in the definition of coastlines with the 25 km data not covering parts of the coastline and some islands. The data was subset into a region covering Scotland to minimise processing and storage requirements, a TIFF raster was produced for each day. To create a dataset with full geographic coverage, nearest neighbour interpolation was performed based upon the surrounding available grid cells to infill the missing areas.

To enable representation of temperature at higher elevations, downscaling was performed using the average environmental lapse rate of -6.5 ° C/km and a 25 km DEM supplied with the temperature data to normalise the original data to a sea level equivalent. Downscaling to 1 km was then performed using the same lapse rate and a 1 km DEM. This approach is somewhat naive as it assumes a constant lapse rate. Greater effort could be applied to improve the robustness of this approach, however, as the implemented snowmelt model is based upon assumed melt factors and there is a lack of data to calibrate the snowmelt model against it as felt that this would not be the best use of available time. The new UKMO temperature data would provide a useful substitute.

3.4.2.1 Validation

To investigate the ability of the 25 km gridded temperature data and the lapse rate assumption to recreate the temperatures found at high elevation in Scotland, pairs of UKMO stations were selected that were close in terms of distance but with large differences in altitude. There are relatively few high elevation stations to choose from and missing data further increases difficulty. However two suitable pairs of stations were found: Aonach Mor (1130 m) and Tulloch Bridge (249 m), Cairngorm Summit (1237 m) and Glenlivet (213) shown in Figure 3.19. These pairs had distances of 15 km and 33 km respectively.

An initial check was performed by applying the lapse rate to the lower station data in an attempt to reproduce the higher elevation data. The result of this is shown in Fig. 3.20. The lapse rate fits the data surprisingly well, however there are some significant errors. Unfortunately there are significant gaps in the gauge records. Other lapse rates between - 5 ° C/km and 8 ° C/km were applied, however, these reduced the fit of the data based upon visual inspection.

Once downscaled using the lapse rate to the 1 km grid, the gridded temperatures were then compared with the 4 met stations (see Figure 3.21). The fit at the lower stations is very good, and the lapse rate will have had a reduced impact. The representation of temperature at higher elevation is poorer with significant over and under-estimation of the measured mean temperature, but the fit is reasonably realistic.

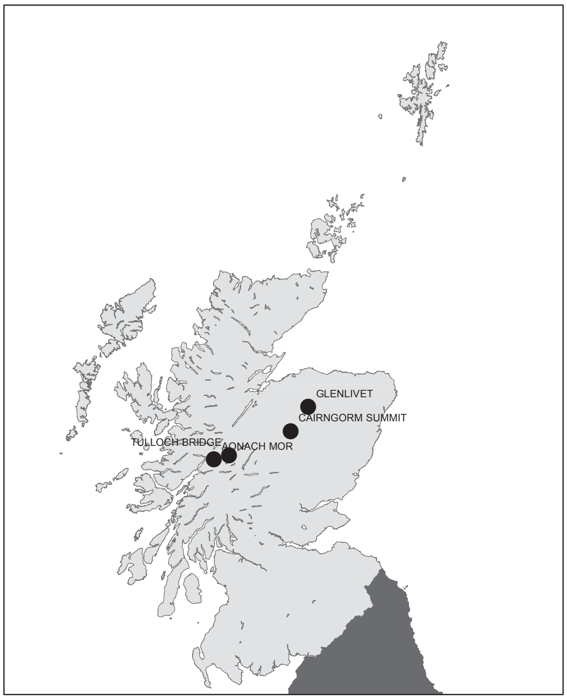

Figure 3.19: Sites used for temperature grid validation

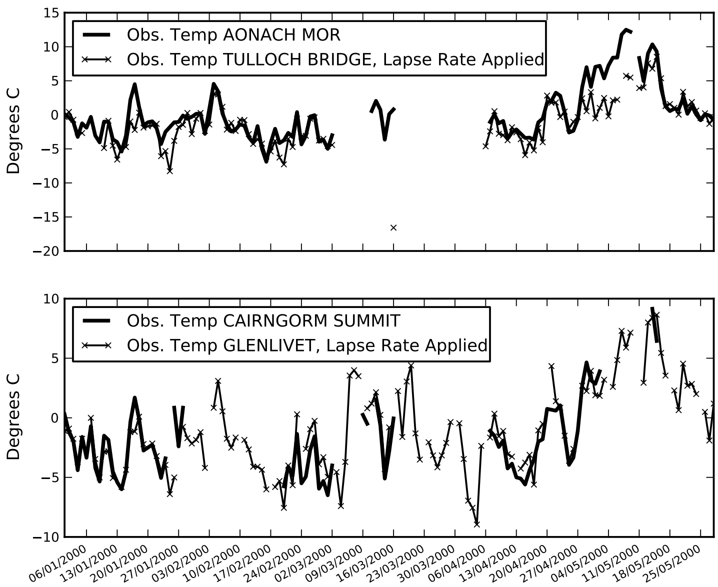

Figure 3.20: Lower station of pair with lapse rate applied plotted against higher elevation station

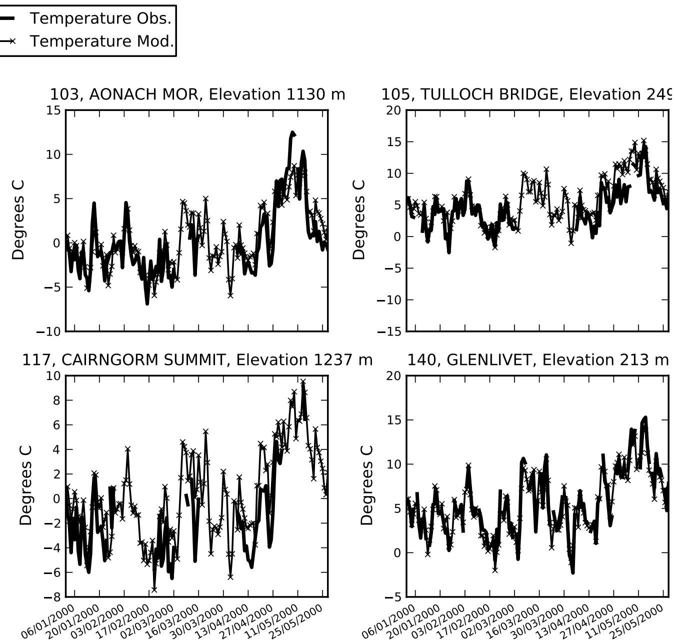

Figure 3.21: ENSEMBLES data with lapse rate applied

3.4.3 Results

The gridding procedure was carried out for the period 1961 - 2006, producing a dataset of daily mean temperature at 1 km resolution with British National Grid projection. An example of typical grids for the first 3 days of 1990 are shown in Figure 3.22. The temperature can be clearly seen to vary with elevation. A simple, but by no means exhaustive, validation has been carried out, however, the method is rather simplistic and could definitely be improved. For the purposes of enabling the use of a simple empirical snowmelt model the data provides a reasonable estimate of upland temperatures.

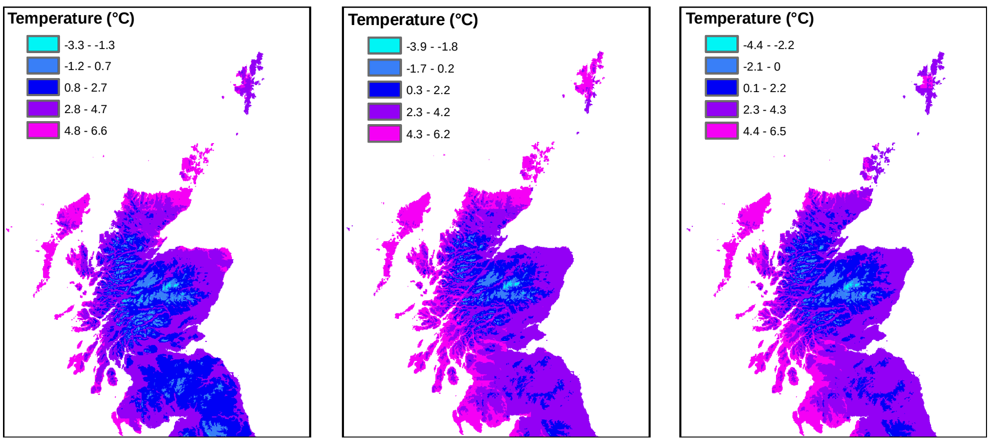

Figure 3.22: Downscaled Temperature grids for 1st to 3rd of January 1990

3.5 Chapter Summary

A comprehensive set of gridded meteorological data has been created for rainfall, PET and temperature. This will be applied in Chapter 5 to force the distributed hydrological model.

4
Development of Hydrological Datasets

4.1 Introduction

A key requirement of any hydrological study is an understanding of the spatial location and layout of the river system being analysed. The simplest form of useful data is the flow-lines and contours available on maps such as the OS Landranger 1:50,000 series, used in this work as a basemap for checking other datasets (OS Landranger, 2009). These features can be used to derive catchment boundaries through identification of minima and maxima, such as ridges along the top of valleys and the outlet from the catchment. Catchment area can then be calculated using a planimeter. Arrows representing the direction of flow on a hillslope can be drawn perpendicularly to contour lines. Simple flow calculations may then be performed using annual rainfall to develop estimates for mean flow. Network descriptions of river systems can be formed by categorising tributaries and the contribution to larger rivers.

Techniques have been developed that allow the extraction of this information from an underlying digital elevation model (DEM) using geospatial processing algorithms. This allows the automated delineation of drainage pathways and catchment boundaries over large areas, further it is possible to then integrate these into a coherent dataset which allows description of the connectivity of river systems.

This chapter introduces these techniques, describes how they were applied and illustrates the three key river network datasets that were produced.

4.2 Extraction of Stream Features from DEM data

Automatic delineation of drainage networks and catchment boundaries from a DEM is a technique regularly applied in hydrology (Bell et al., 2007a; Dunn and McAlister, 1998; Young et al., 2003). HYDRO1K, for example, provides a continental scale hydrological dataset of streamlines and catchment boundaries developed from a global DEM (Danielson, 1996). The majority of approaches use a variant of the 'D8' algorithm developed by O'Callaghan and Mark (1984) which allows the creation of complex and accurate hydrological networks using relatively simple GIS techniques. This method allows the automatic generation of rasters detailing flow pathways, measures of catchment area and catchment boundaries. These can be subsequently converted to polyline and polygon representations of a hydrological system. Rasters of flow directions can be used by hydrological models to perform flow routing, this approach has been used with the G2G Hydrological model as part of this project and is discussed in the next chapter.

4.3 D8 Algorithm

The D8 algorithm allows the hillslope flow across the surface of the DEM to be categorised into one of 8 directions, these flow directions can then be used to compute the accumulation of surface flow to identify streams and rivers and define catchments.

Underpinning the D8 algorithm is the use of DEM derived slope estimates, calculated for an individual DEM cell by fitting a plane to the z values (height) of the surrounding 8 cells. From slope values aspect can be derived, this is the direction of slope identified as the steepest downslope direction from each cell to its neighbours. By assuming that flow on a hillslope will follow the steepest path, slope aspect can be treated as a proxy for flow direction (see Fig. 4.1).

By identifying cells with no inflow from other cells, catchment boundaries can be established, moving from these maxima cells downstream following the flow direction value it is possible to iteratively accumulate the number of upstream cells that feed in to a particular cell. This provides a measure of the catchment area upstream of a cell. Fluvial features can then be defined by specifying an accumulated area threshold, defining cells fed by enough upstream area as streams and rivers. When a tributary reaches a higher order river there will be a large difference between the accumulated flow of each. This can be used to identify confluences and the outlets of sub-catchments.

4.4 Flats and Sinks

Difficulties are encountered with errors in DEM data introduced by the measurement and processing techniques used during construction, with pits or sinks (where one cell is surrounded by

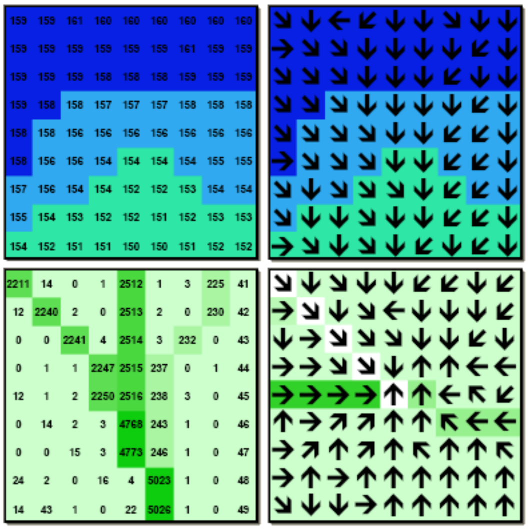

Figure 4.1: Example of 10 m DEM data converted to flow direction and flow accumulation using D8 algorithm

higher elevation cells) in the data making algorithms difficult to apply. Because of the reliance on gradient as a proxy for flow direction further problems are encountered when dealing with areas of flat terrain, including DEM representation of waterbodies. Several techniques involving data manipulation such as smoothing filters attempt to overcome this with partial success. A more successful approach involves the use of sink filling algorithms that increase the values of cells in a depression to the level of the lowest cell on the depression's boundary (Martz and Garbrecht, 1999). The use of stream lines to 'burn' channels into a DEM before application of sink filling and the D8 algorithm is shown to provide satisfactory results in flat areas, including waterbodies, allowing the developed network to have improved spatial accuracy. Hellweger (1997) further developed this concept with the AGREE algorithm which burns a stream network into the DEM a number of cells wide as a V-shaped notch.

4.5 Limitations of D8

Although simple and robust, once the data has been adequately prepared, the D8 method has some limitations, the main one being that reduction of flow direction into 8 directions does not ideally represent the physical flow of water across a slope. More complex methods such as 'Dinf', where water can flow in different proportions into all neighbouring cells, have been developed which enable more realistic (albeit complex) representation. As the D8 method designates cells as being 'river' or 'not river' it becomes difficult to accurately represent the

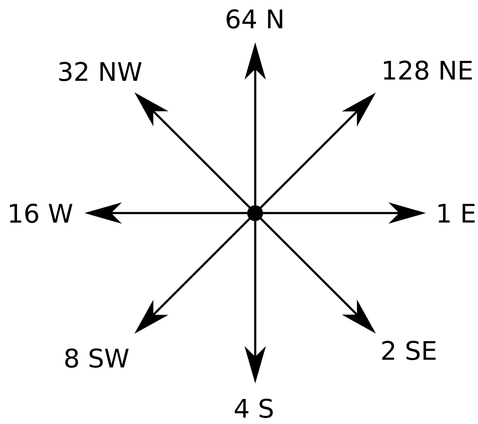

Figure 4.2: Flow directions and associated integer values used by D8 algorithm

geographical location of derived river systems when using coarser DEM data. The actual width and profile rivers is also ignored, with all derived rivers effectively having the same width.

4.6 Dendritic Network

Dendritic systems (from the Greek "of or pertaining to a tree") consist of small tributaries that converge to form larger streams and then major rivers. These are the most common forms of river system although others such as braided streams, or trellis systems are found in areas of marshland or areas with specific geological formations. Dendritic systems are common in V-shaped valleys with impervious rock and can be found throughout Scotland. This is the only network type that has been considered in this study.

The dendritic model is a useful model of connectivity as the river systems can be represented with simple vector polylines and assigned clear hierarchy.

4.7 Stream Order and River Addressing

The Strahler stream order is a measure of a dendritic network's branching complexity. The smallest streams with no upstream tributaries are termed order 1; these converge to form order 2 streams and so on. A very complex network such as the Amazon reaches order 12 at its mouth. To enable this model there can be no parallel or 'braided' streams; additionally rivers are assigned a single path through water-bodies, depicted by a centreline.

Reaches can be assigned an address. It is possible to associate the address for the next downstream reach of higher order with the upstream reach. The location along the reach, typically referred to as chaining can also be defined. This provides a simple method to locate a position on a river and also to trace the flow from the top of a catchment downstream and eventually to the sea.

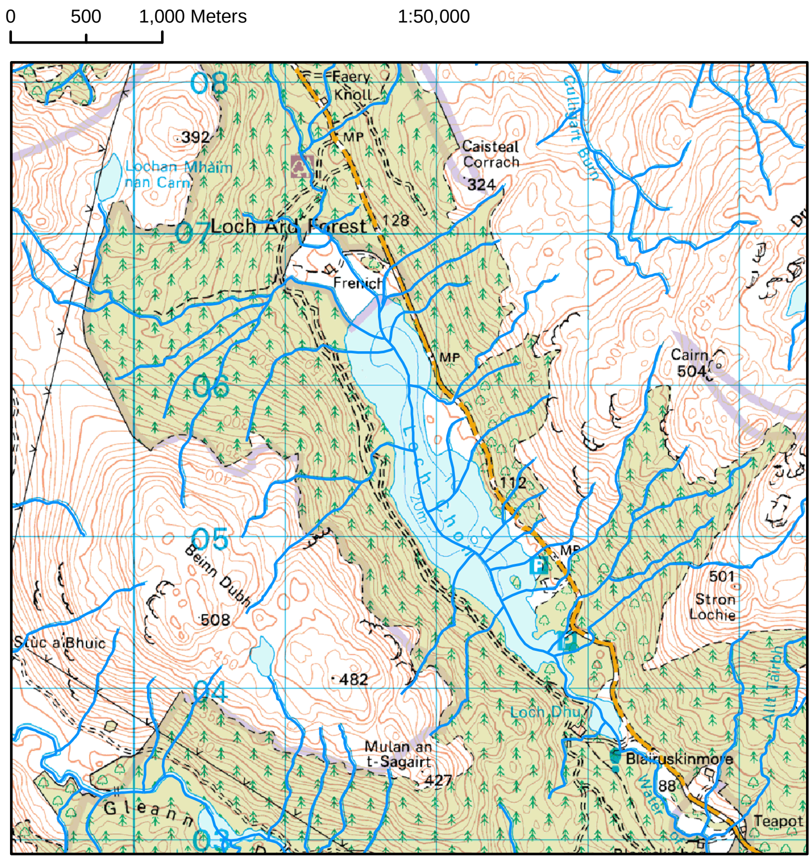

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Figure 4.3: CEH vector rivers dataset waterbody centreline

4.8 Arc Hydro Model

Several packages are available that implement the discussed methods.

The GRASS package is an open source GIS that contains a variety of methods including the D8 and Dinf methods. While suitable for small areas, it was found that the algorithms were not especially robust when working with larger datasets. The TerraStream algorithm has been designed specifically to enable processing of very large grids, with order of tens of GB. This was found to provide good results however the sink filling algorithm lacked control and produced unsatisfactory results.

The Arc Hydro model provides robust algorithms. Choices of routing algorithm are more limited than GRASS and not as scalable as TerraStream, however with appropriate subdivision of datasets can perform well on medium sized grids. In addition to DEM feature extraction methods Arc Hydro provides functionality that enables development of a fully addressed database implemented vector river network. This final feature made Arc Hydro a clear choice over the alternatives as it enables development of a hydro search method based upon SQL database queries.

Stream lines and catchments are addressed using what is termed the 'HydroID'. Each stream reach is assigned a unique HydroID and is stored in the record describing each item. The HydroID of the next downstream reach (the NextDownID) is also recorded in each reaches record, with outlets to the sea assigned a NextDownID of -1. This enables network analysis to be performed upon the river system, providing the ability to trace the flow of water from an upland stream through confluences forming major rivers finally reaching the sea. River reaches can also be split into steps, and assigned a StepID enabling full addressing of flow pathways. This concept forms the basis for development of a hydro search routine in Chapter 6.

A wide range of hydrological detail can be combined on top of the basic centreline network model, including bank lines, cross sections, weirs, shorelines and gauging station locations. This offers the possibility of creating a full hydraulic model of a region that can then be used as input to a hydrological model. The ability to create a consistent data model including hydraulic features built using centre lines (Thalweg lines) and cross-sections is very appealing and would facilitate sophisticated hydrological modelling using 3 dimensional hydraulic flow routing methods.

Only the more basic functionality of the model has been used in this project. One major constraint is the lack of river profile lines. Several techniques have been shown to enable generation of profile lines using high resolution aerial photography. Using the OS Mastermap Aerial photography layer could enable this. This would offer a very powerful tool when combined with an appropriate hydrological model for flood analysis.

4.9 Available Data and Resolution

The DEMs described in Chapter 2 section 2.8 are available for use. It was decided to use the OS Profile 10 m to develop a hydrological dataset at this resolution, and to use the OS Panorama 50 m dataset to develop a lower resolution 200 m dataset for use with the G2G hydrological model (OS Panorama, 2009; OS Profile, 2009).

CEH have developed a vector river network dataset based upon Ordnance Survey 1:50,000 mapping (CEH, 2008c). This dataset consists of continuous centre-line representations of river systems, this includes centre-line representation of flow through waterbodies as shown in Figure 4.3. While generally very accurate - the dataset provides an extremely dense representation of Scotland's river network - there are systematic errors that have been introduced by the scanning method used to produce the dataset. There is a degree of misalignment between the vector river dataset and original OS 1:50,000 maps. The level of error does not exceed 50 m and in most instances is significantly less than this (see Figure 4.4).

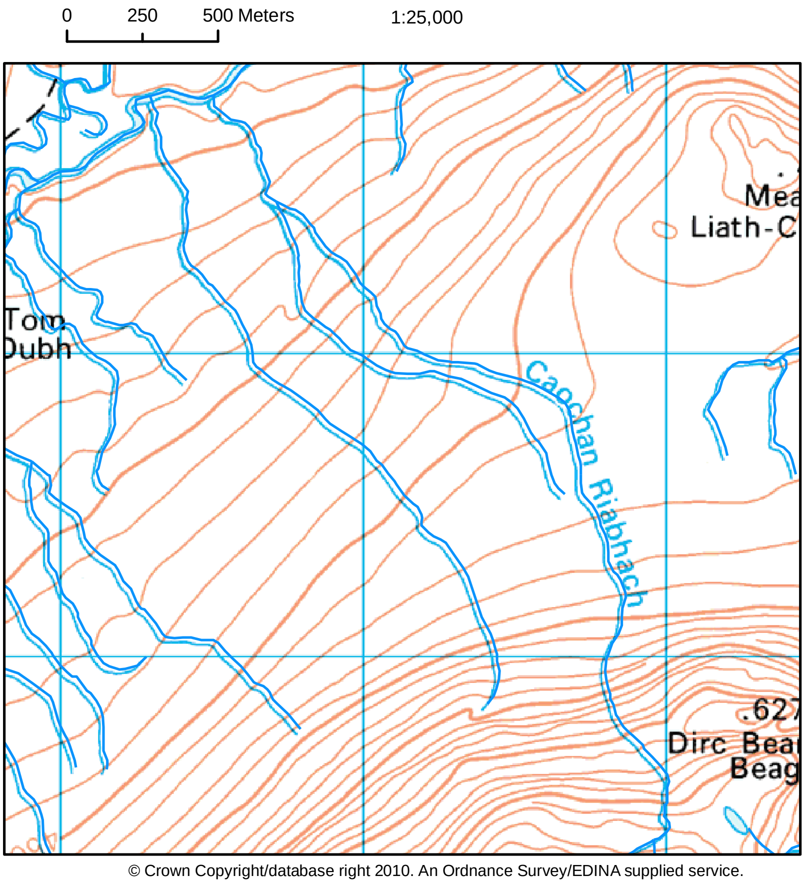


Figure 4.4: Example of discrepancy in CEH rivers dataset

4.10 Impact of Data Resolution

The choice of DEM resolution has great impact upon the ability to realistically represent river networks. Figure 4.5 shows a catchment and streamlines derived from DEMs at 1 km, 200 m and 10 m resolution. The approximation becomes much better as the resolution increases. The greatest difference can be seen in the catchments headwaters with major tributaries better represented. Operating at higher resolution requires much greater computational expense, with 200 m data 25 times greater in density than 1 km data and 10 m data 400 times greater in density than 200 m data.

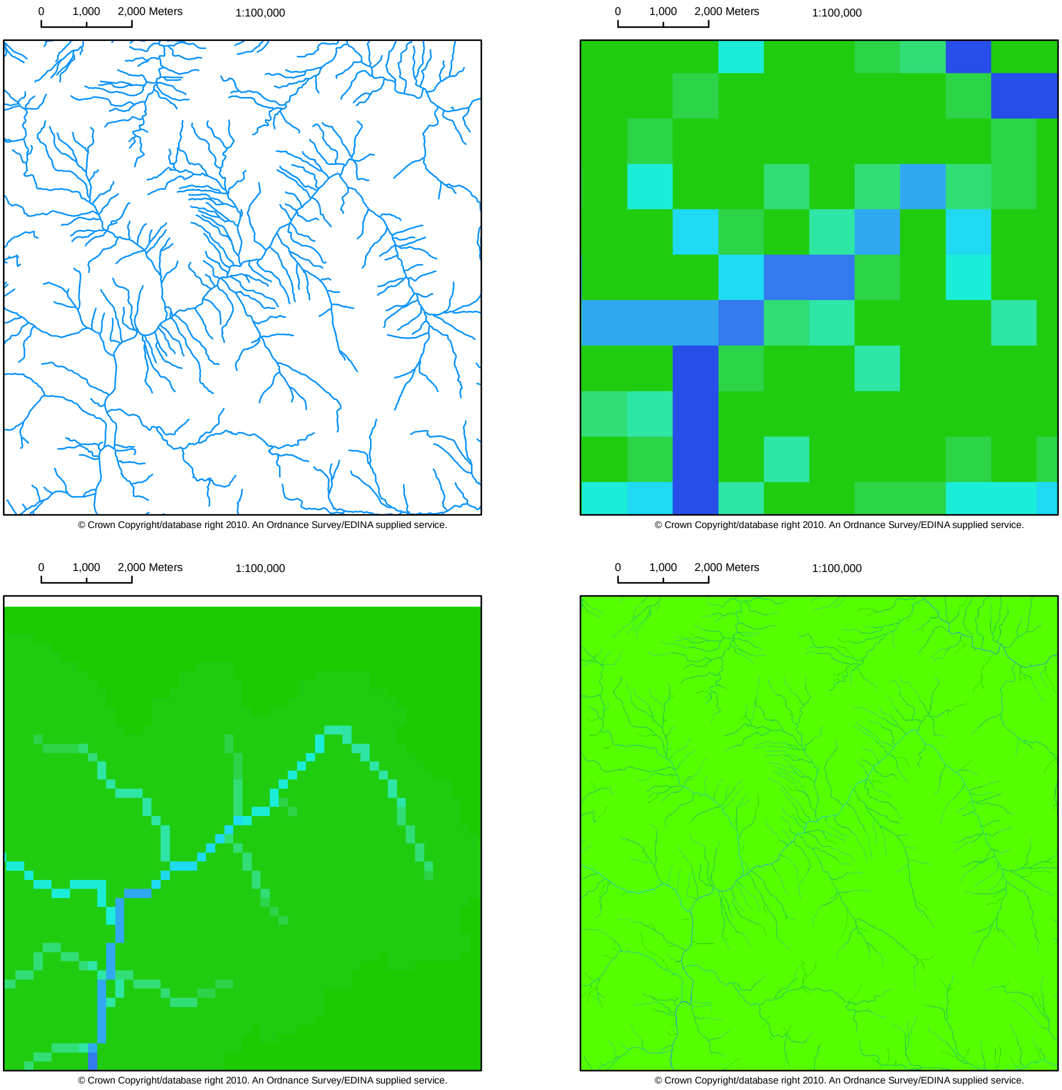


Figure 4.5: a) CEH vector streamlines; b) 1 km derived flow pathways; c) 200 m DEM derived flow pathways; d) 10 m DEM derived flow pathways

McMaster (2002) analysed the impact of DEM resolution on the ability to reproduce stream networks using both Dinf and D8 methods, and found that the ability to produce accurate stream networks (when compared to mapped streamlines) dramatically reduced as grid size increased above a threshold of 180 m with the most dramatic decreases in fidelity occurring between 200 m and 400 m grid sizes. Based upon his findings a 200 m grid size is appropriate and allows simple area averaged aggregation from a 50 m grid. Despite the difficulty of modelling smaller headwater catchments accurately, river networks derived from a 1 km resolution DEM are suitable for representing larger catchment areas as illustrated in Figure 4.6. The choice of minimum catchment area also has a significant impact upon the complexity of generated results. The CEH rivers dataset has a very high level of spatial detail, including headwater streams with very small catchment areas. If a minimum threshold of 1 km^2 is applied, a large number of these are removed, significantly reducing the size and complexity of the dataset.

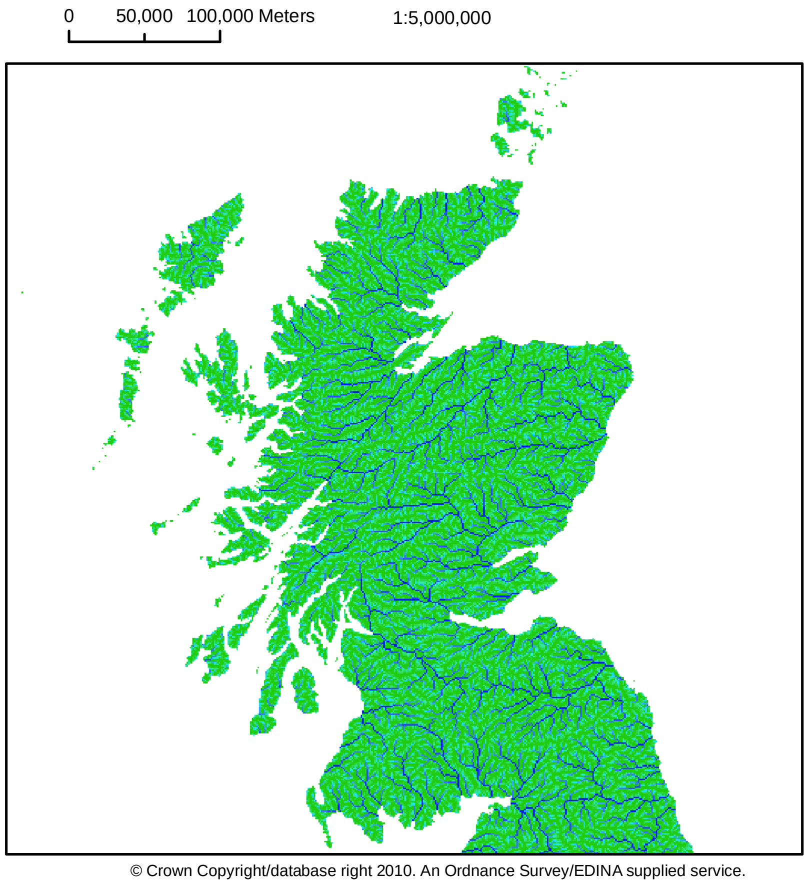


Figure 4.6: Flow accumulation grid derived from 1 km DEM

4.11 Hydrometric Areas

The UK has been subdivided into Hydrometric Areas (HA), distinct hydrological regions which consist of either a single large river system ,for example the Clyde or the Tay, or areas of consistent hydrology made up of smaller catchments, such as on the west coast of Scotland. The areas provide a convenient means of subdividing the problem of modelling Scotland's rivers into more convenient sizes. The areas range in size with the River Tay the largest at approximately 5000 km^2.

4.12 Outline of General Procedure

Application of the Arc Hydro model can be split into three sections: DEM preparation, terrain analysis and a final vector based network analysis to ascribe stream orders and connectivity details to the dataset. These are summarised in Figure 4.7.

4.12.1 Fionn Glheann catchment

The procedure used to develop the hydrometric datasets is illustrated based upon the Fionn Glheann catchment, a small (11 km^2) tributary of the River Falloch in the Trossachs region. This catchment was chosen as it is the site proposed for a small run-of-river hydro scheme, and because its scale can be used to illustrate some of the problems experienced when using lower resolution data to represent smaller upland catchments. The catchment is typical of those found in the Scottish Highlands featuring numerous ephemeral streams which are likely only visible during times of peak flow. Figure 4.8 shows the OS representation of the catchment. It is testament to the tenacity of OS surveyors that such level of hydrological detail has been included.

4.12.2 Determining flow direction from elevation

The catchment is steep with elevation falling from over 600 m to 30 m over a distance of approx 8 km. Figure 4.9 shows the raw 10 m DEM depiction of the catchment. This figure was developed by applying a hill-shade to the DEM along with a classified colour surface.

The slope and aspect are subsequently derived and used to estimate hill-slope flow direction.

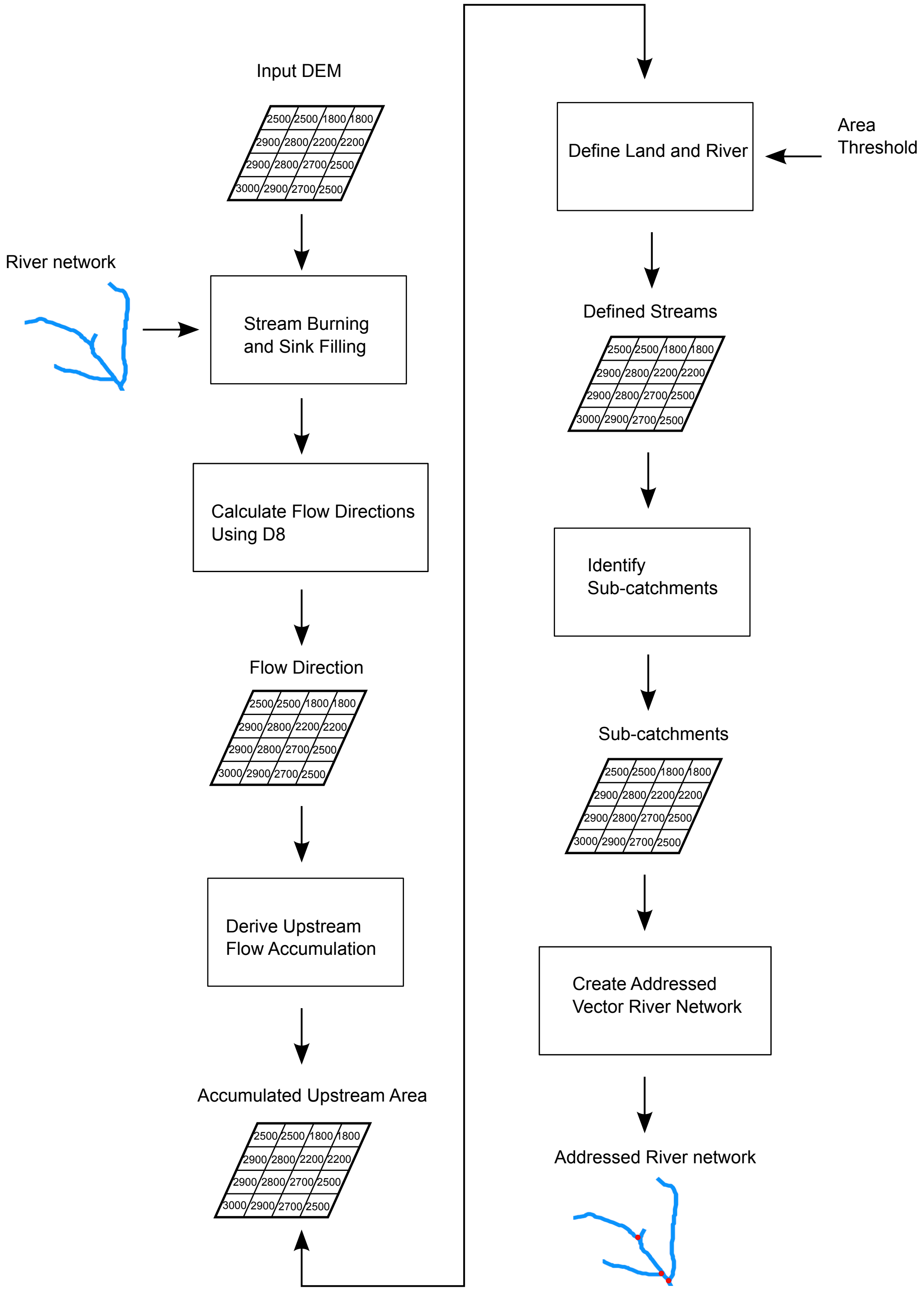


Figure 4.7: Overview of processing procedure

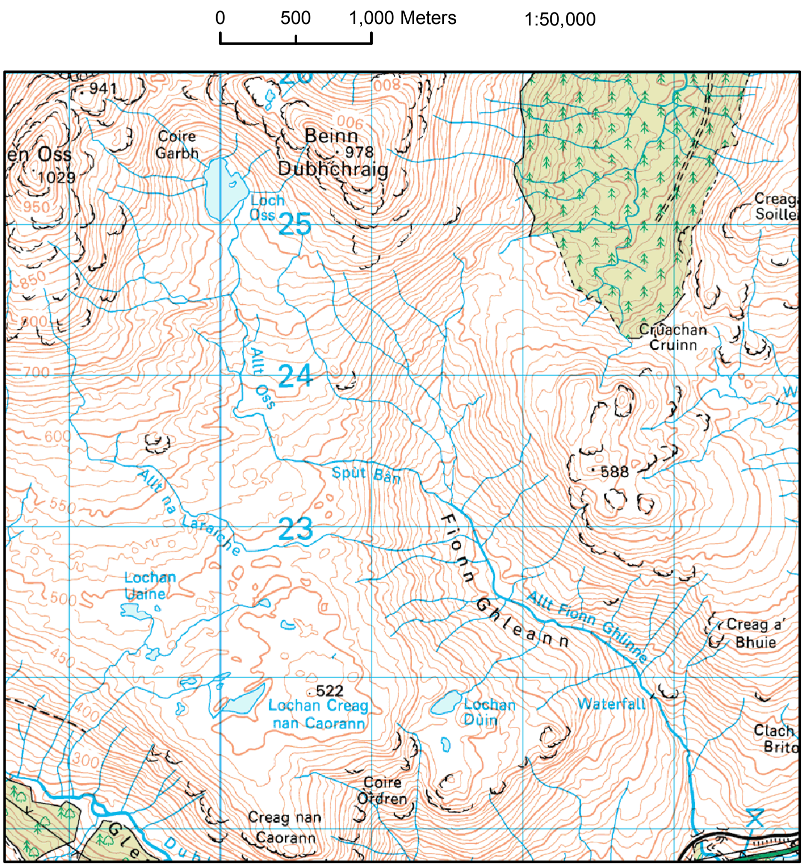


Figure 4.8: Ordnance Survey Landranger depiction of the Fionn Glheann catchment

This is shown in Figure 4.10. The direction of slopes classified into 1 of 8 compass directions can be seen. The flow direction is then traced and accumulated, allowing the location of river and stream pathways to be delineated.

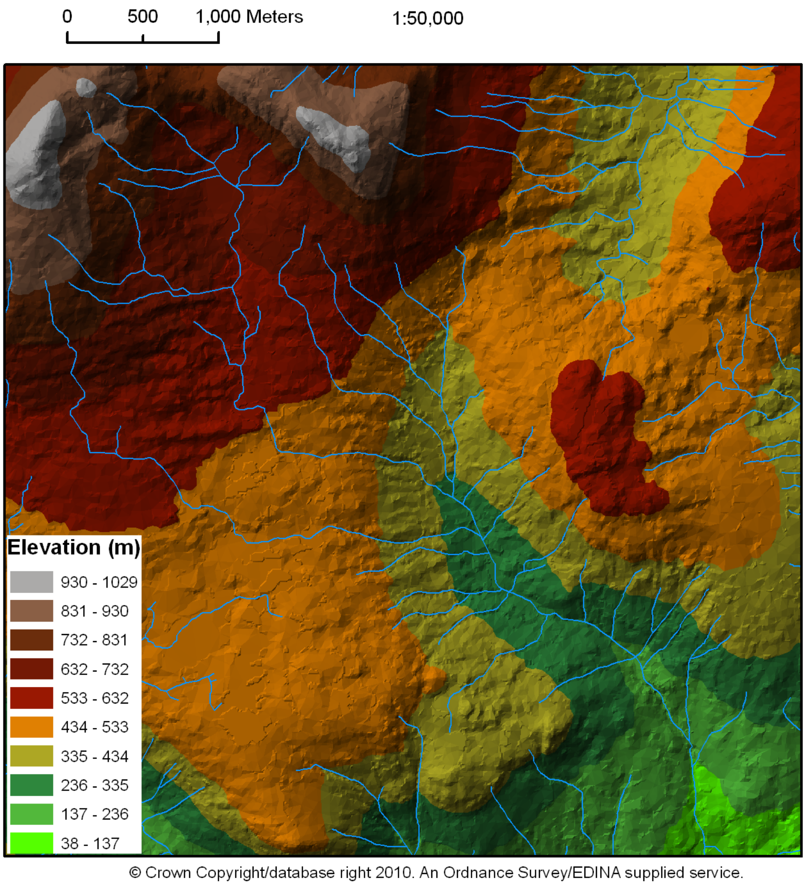


Figure 4.9: Shaded 10 m DEM overlayed with CEH vector rivers dataset

The level of accumulation increases logarithmically, from areas with very little upstream inflow, on the order of tens of cells to main flow pathways with millions of upstream cells. By applying a minimum threshold to the flow accumulation grid it is possible to classify what will be treated as a flow pathway and what will be treated as land.

4.12.3 Overcoming DEM errors

Measurement and interpolation errors incorporated in the DEM can cause the creation of flow sinks, requiring pretreatment before the DEM can be used. Sinks cause problems as flow pathways are disrupted and with flow 'disappearing'.

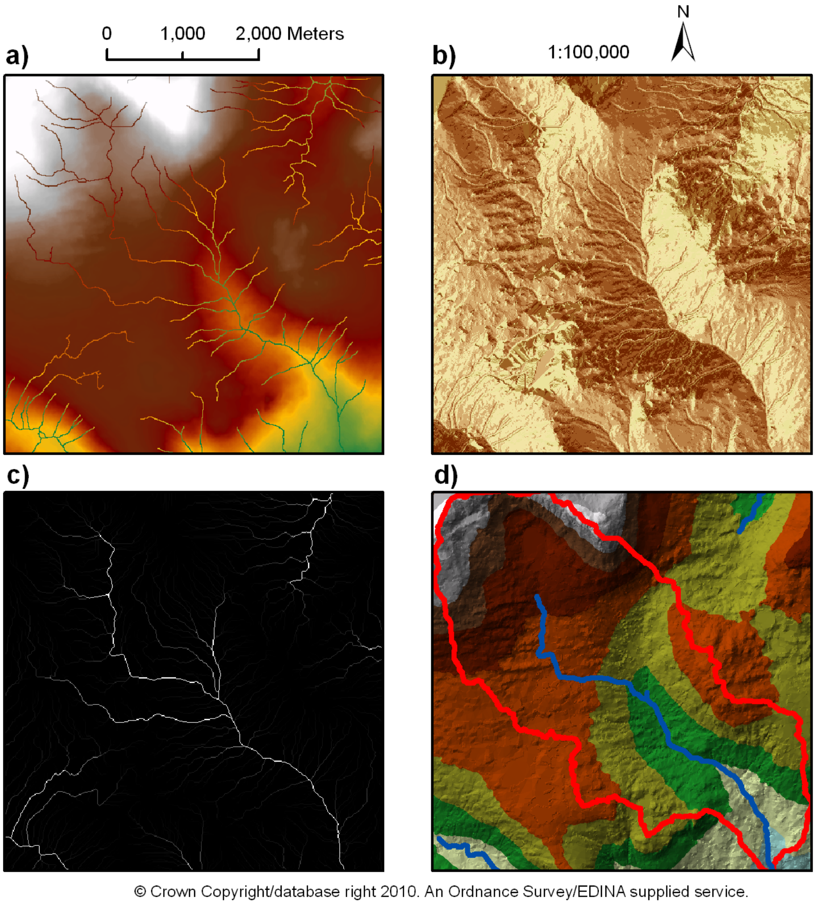


Figure 4.10: **a)** Burning vector river network into DEM and using sink filling algorithm enables accurate representation of flow-paths; **b)** Calculation of slope and aspect allows flow direction to be assigned; **c)** Cells that flow into adjacent downstream cells are accumulated giving the catchment area at a point; **d)** Flow-paths converted to vector river network using minimum threshold of 2 km^2 (20,000 cells). Catchment area derived based upon local maxima.

The use of CEH vector river sets developed from OS 1:50,000 flow-lines to burn in channels to the DEM allows better geographic representation of the river network. This also has the added advantage of improving the hydrological consistency of the dataset. Further hole filling completes the raster preparation allowing the flow routing procedure to be successfully completed. Holes are removed using a sink filling function raising the elevation of cells in identified holes to the elevation of surrounding cells.

4.12.4 Identifying river pathways

Choice of threshold for river pathways is somewhat arbitrary, however using a process of trial and error a minimum threshold of 20,000 cells or 2 km^2 was chosen. It was found that values lower than this, while still accurate, produced very dense stream networks, requiring far greater processing times due to the significantly greater numbers of lower order streams. While this effectively excludes catchment areas of less than 2 km^2 from analysis, it was felt that this was an acceptable compromise as it greatly improved the tractability of the problem, at the expense of not identifying small sites, which would likely be marginally economic at best. Development of a simplified vector river dataset would then be subsequently used when developing the lower resolution dataset.

4.12.5 Delineating catchment areas

After applying the threshold the streams are represented on a 10 m raster as lines a single cell wide. This is processed to identify connecting stream lines. These points of confluence can then be treated as the outflow points for sub-catchments for subsequent processing. By utilising the flow direction raster and the using these points it possible to trace back upstream until the catchment boundary is found. With vectorisation of the streamlines and catchment boundaries it is then possible to build a river network database.

4.12.6 Difficulties Encountered

Maidment (2002) recommends using a deep burning depth when performing DEM reconditioning using vector streamlines. It was found that when a large depth was applied when burning the CEH vector rivers dataset that streams would be incorrectly routed into the wrong catchment. This was caused by the CEH rivers being “too good”, with stream lines extending to the

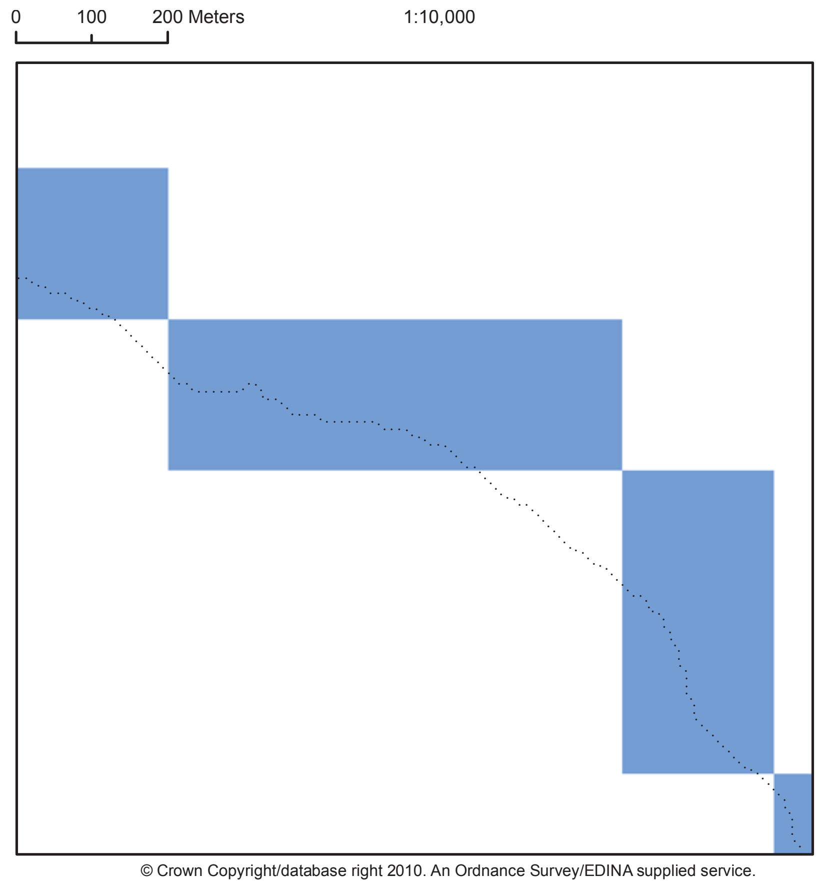


Figure 4.11: Inconsistencies between stream network addressed at 10 m intervals and flow pathways at 200 m

catchment boundary. This caused streamlines in neighbouring catchments lying within several DEM cells of each other to be considered as a single flow path. This in turn led to the sink filling algorithm incorrectly filling the streams causing them to be routed together. Significant manual editing of the CEH vectors dataset was required. The tops of reaches clearly in separate catchments that lay in close proximity were edited to increase the distance between them to several hundred meters. This was found to adequately solve the problem.

The definition of shorelines was found to be an issue particularly in tidal areas with large beaches. The CEH vector rivers dataset was found not to extend to the boundary of the DEM, in these circumstances delineated streams would not reach the edge of the DEM. The sink filling algorithm would then tend to route streams behind the boundary leading to situations where streams would be routed behind a beach. This problem was again solved by manual editing of the rivers dataset. The stream features close to shorelines were extended over the boundary of the DEM, effectively into the sea.

4.12.7 Scaling up

When performing this processing nationwide it was necessary to use a divide-and-conquer approach. The original Scotland-wide 10 m DEM is approximately 12 GB in size, far greater than the memory available for processing using ArcGIS. This causes the GIS software to rely upon parsing from the hard disc which severely impedes compute times.

The country was split using hydrometric areas as designated by CEH, typically consisting of one large river system such as the Tay or Spey, or areas of consistent hydrology made up of smaller catchments such as on the west coast (CEH, 2008b). All areas are effectively hydrologically separate with boundaries derived at the edges between catchments.

DEMs for each hydrometric area were prepared and processed producing a vector river network for each at 10 m. These vector networks were then used to perform the method again at 200 m, producing 200 m vector networks for all hydrometric areas.

4.13 Final Datasets

The process of delineating catchment and streamline networks from DEM data has been discussed using the OS Profile 10 m DEM as an example.

Three distinct hydrometric datasets have been developed using different DEM resolutions as indicated in Table 4.1. An initial coarse dataset based upon a 1 km DEM was created to enable hydrological model development, testing and calibration. This was used to develop models of gauged catchments: the catchment boundaries upstream of the gauge location were calculated and delineated; these were then used to extract grid data for each gauged catchment (see Figure 4.12). A higher resolution dataset with national coverage split by hydrometric area was created using a 200 m DEM for use with the finalised calibrated hydrological model. The choice of 200 m was found to provide a compromise between model run-times and the accuracy with which small upland catchments could be portrayed. Finally a very high resolution dataset was created from a 10 m DEM. This high resolution dataset was used to create the river network used to populate the hydro-search database, and burn the 200 m dataset. This high resolution dataset was chosen because it allowed very accurate representation of OS 1:50,000 scale streamlines and would enable high accuracy head estimates using the 10 m Profile DEM (see Figure 4.13). The raster flow direction data was used to search for impoundable locations, although this could have been feasibly achieved at a lower resolution as this analysis was temporally static the use of high resolution data does not have the same impact on run-times.

Dataset	**Input DEM**	**Input Streamlines**	**Land/River Threshold**	**DEM Subdivision**	**Use**
High resolution (10 m)	OS Profile (10 m)	CEH Streamlines	20000 cells (2 km^2)	Hydrometric area	Addressed river network for hydro search, simplification of CEH streamlines
Medium resolution (200 m)	OS Panorama (50 m)	High resolution streamlines	800 cells (2 km^2)	Hydrometric area	Final hydrological modelling for hydro search
Low resolution (1 km)	OS Panorama (50 m)	High resolution streamlines	2 cells (2 km^2)	No subdivison	Initial model development calibration and validation

Table 4.1: Summary of high, medium and low resolution datasets

4.13.1 Development of complete rivers dataset

The high resolution river network was attributed points at 10 m intervals along stream reaches, these were then assigned key attributes such as elevation, upstream catchment area, HydroID and a stepID describing how far down a reach the point was. These datasets together with modelled flows at each of these points form the basis of the hydropower search database (Chapter 6).

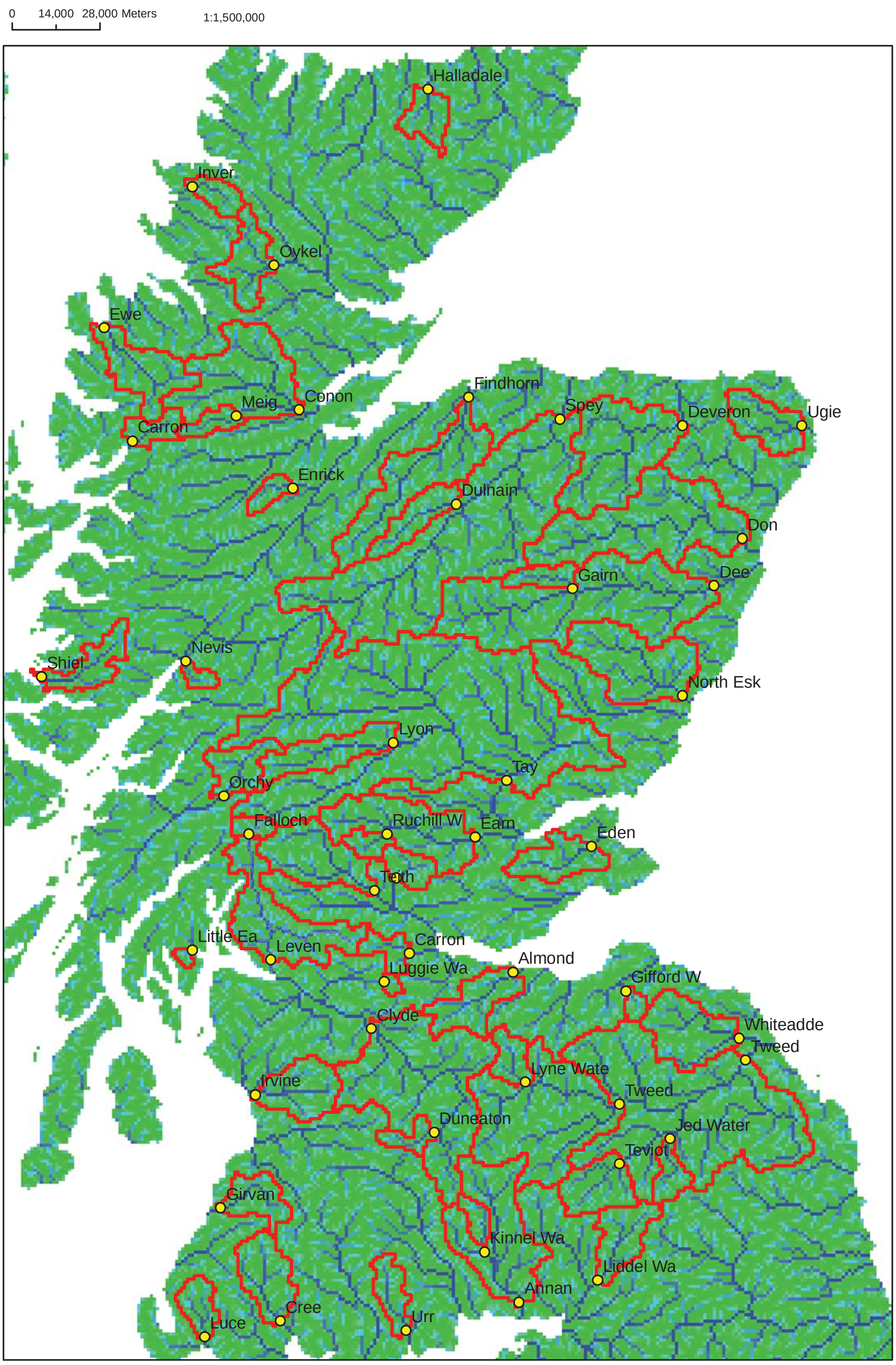


Figure 4.12: Gauged catchments with boundaries delineated from 1 km DEM

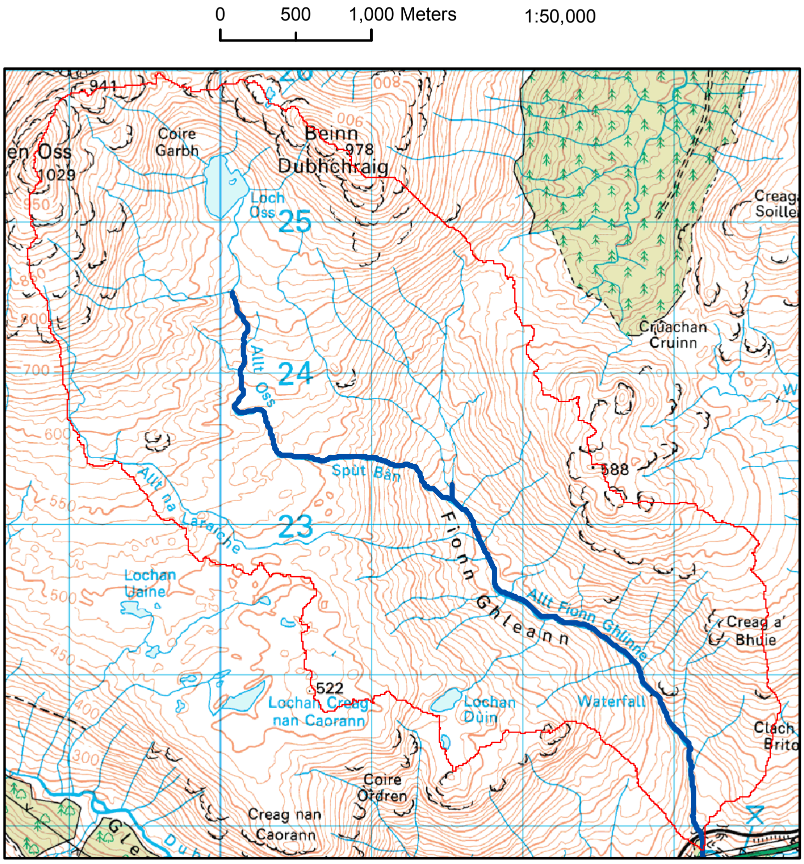


Figure 4.13: Good accuracy is maintained between derived network and OS Landranger, catchment area corresponds to mapped peaks

4.14 Validation and discussion of errors

While enabling different levels of analysis the use of data with different underlying spatial resolution poses some problems. The ability to transfer a parametrisation from a hydrological model operating at one resolution to another is potentially challenging. Streamlines derived from a DEM can only ever be an approximate model of reality (improving with higher resolution of course). When overlaid, streamlines developed from different DEM scales will tend not line up exactly. This posed a problem when extracting flow time series from the hydrological model at 200 m to apply to the hydro search database at 10 m (see Figure 4.11).

When used with 10 m DEM data the Arc Hydro D8 process produces results which are consistent with OS landranger. There is some error in terms of geographic location of stream-lines, this is typically less than 10%, increasing to 20% in some situations. In terms of hydrological accuracy a comparison was made between the stated catchment areas of CEH gauge stations and the estimated catchment area produced from the 1 km dataset. Table 5.5 shows that there is generally good agreement with an average error of 3.3% increasing above 10% for certain catchments (generally featuring relatively flat areas) where the process has incorrectly routed certain streams.

4.15 Chapter Summary

This chapter describes the process used to develop detailed spatial representations of Scottish hydrology at differing resolutions. Flow direction and accumulation grids have been developed at 1 km and 200 m resolution for use with the G2G model, described in the following chapter. A high resolution river network dataset has been created from 10 m DEM data for use with the hydropower search method described in Chapter 6.

Gauge Number	River	Location	Published Catchment Area (km^2)	Estimated Catchment Area (km^2)	Error (%)
3003	Oykel	Easter Turnaig	330.7	324	2.0
4001	Conon	Moy Bridge	961.8	972	1.1
4005	Meig	Glenmeannie	120.5	118	2.1
6008	Enrick	Mill of Tore	105.9	98	7.5
7002	Findhorn	Forres	781.9	795	1.7
8006	Spey	Boat o Brig	2861.2	2897	1.3
8009	Dulnain	Balnaan Bridge	272.2	272	0.1
9002	Deveron	Muiresk	954.9	936	2.0
10002	Ugie	Inverugie	325	328	0.9
11001	Don	Parkhill	1273	1277	0.3
12002	Dee	Park	1844	1859	0.8
12006	Gairn	Invergairn	150	144	4.0
13007	North Esk	Logie Mill	732	737	0.7
14001	Eden	Kemback	307.4	310	0.8
15006	Tay	Ballathie	4587.1	4574	0.3
15011	Lyon	Comrie Bridge	391.1	391	0.0
16003	Ruchill W	Cultybraggan	99.5	103	3.5
16004	Earn	Forteviot Bridge	782.2	787	0.6
17001	Carron	Headswood	122.3	136	11.2
18001	Allan Water	Kinbuck	161	159	1.2
18003	Teith	Bridge of Teith	517.7	522	0.8
19001	Almond	Craigiehall	369	361	2.2
20007	Gifford W	Lennoxlove	64	59	7.8
21006	Tweed	Boleside	1500	1494	0.4
21009	Tweed	Norham	4390	4414	0.5
21012	Teviot	Hawick	323	342	5.9
21018	Lyne Water	Lyne Station	175	170	2.9
21022	Whiteadde	Hutton Castle	503	495	1.6
21024	Jed Water	Jedburgh	139	155	11.5
77003	Liddel Water	Rowanburnfoot	319	316	0.9
78003	Annan	Brydekirk	925	950	2.7
78004	Kinnel Water	Redhall	76.1	99	30.1
80001	Urr	Dalbeattie	199	195	2.0
81002	Cree	Newton Stewart	368	369	0.3
81003	Luce	Airyhemming	171	173	1.2
82001	Girvan	Robstone	245.5	245	0.2
83005	Irvine	Shewalton	380.7	376	1.2
84005	Clyde	Blairston	1704.2	1682	1.3
84016	Luggie Water	Condorrat	33.9	33	2.7
84022	Duneaton	Maidencots	110.3	111	0.6
85001	Leven	Linnbrane	784.3	819	4.4
85003	Falloch	Glen Falloch	80.3	82	2.1
86001	Little Ea	Dalinlongart	30.8	27	12.3
89003	Orchy	Glen Orchy	251.2	261	3.9
90003	Nevis	Claggan	69.2	65	6.1
92001	Shiel	Shielfoot	256	264	3.1
93001	Carron	New Kelso	137.8	146	6.0
94001	Ewe	Poolewe	441.1	449	1.8
95001	Inver	Little Assynt	137.5	141	2.5
96001	Halladale	Halladale	204.6	208	1.7
				Average % Error	3.3

Table 4.2: Comparison between derived catchment area and measured catchment area

5
Development, Calibration and Validation of Grid Based Hydrological Model

5.1 Introduction

This chapter details the development of an implementation of the G2G model, a conceptual distributed hydrological model. After assessing available model options (see Chapter 2), the G2G model was chosen because of its relative simplicity, proven ability to simulate flows across the UK at high resolution and ease of integration with GIS datasets. Unfortunately this model has not been disseminated publicly and is currently being developed for commercial use by CEH Wallingford. Therefore a model code has been developed based upon published details of the model structure. Although time consuming (compared to use of a pre-existing code), development of custom code enabled batch use with a pool of UNIX machines. This allowed long time series of flows distributed across the Scottish river network to be computed and Monte Carlo methods to be employed that would not be possible using a single desktop machine. A 1 km spatial resolution version of the model was validated against available SEPA river gauge data using individual catchment calibrations developed using the shuffled complex evolutionary algorithm (SCE-UA). A simple regionalisation approach was then applied to produce regional model calibrations using a Monte Carlo method. To investigate the impact of likelihood function on resulting calibration two likelihood functions were used independently and the resulting FDCs compared. The model was then operated Scotland-wide to produce time-series flows for the period 1961-2005 at 200 m resolution. To investigate parameter uncertainty the generalised uncertainty estimation (GLUE) method was used to produce cumulative distribution functions (CDFs) of parameter performance allowing bounded hydrographs to be developed.

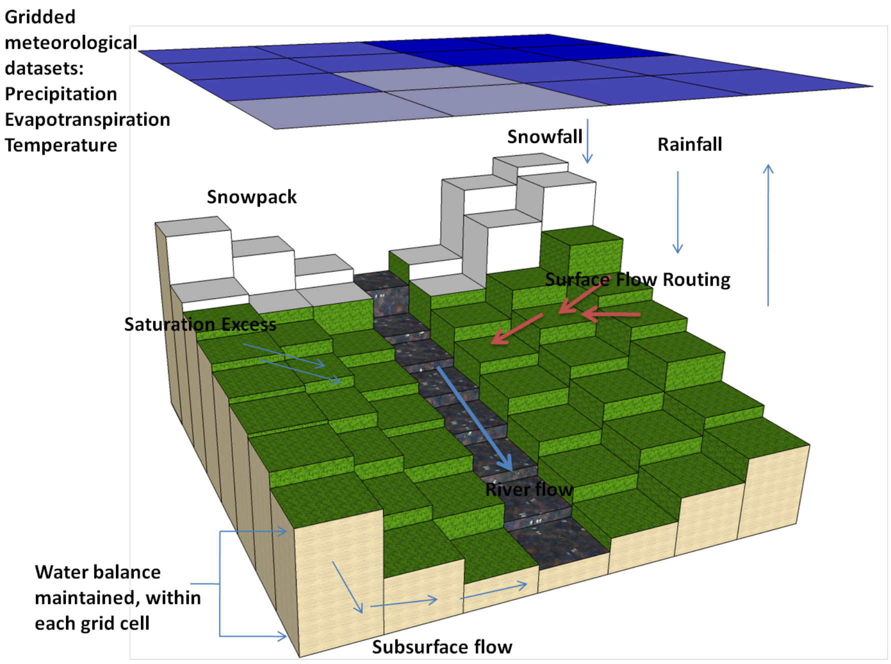


Figure 5.1: Illustration of the G2G model structure

5.2 Model Structure

5.2.1 Overview

The G2G model was developed to simulate river flows over large regional domains at a relatively high 1 km × 1 km resolution using grid based meteorological and climate model data (Bell et al., 2007a,b). The model has been applied at 1 km resolution across the whole UK to assess the impact of climate change upon flood frequency (Bell et al., 2007b) and used with sub daily rainfall radar data (Cole and Moore, 2008). The G2G model is a further development of the CEH grid model and utilises the same runoff production mechanism (Bell and Moore, 1998). The model structure presented here,with the exception of the snowmelt model, is based upon Bell et al. (2007a).

The runoff production mechanism employed by the G2G model makes use of a probability distributed moisture store to represent the heterogeneity and dynamic response of partially saturated catchments. This approach was first proposed by Zhao (1977) who showed that runoff generation in humid Chinese catchments could be successfully represented by a spatially variable moisture store controlled by a probability distribution function. The Xinanjiang model was developed based on this concept and has been widely applied within China (Ren-Jun, 1992).

A similar approach was proposed by Moore and Clarke (1981) leading to development of the PDM model (Moore, 1985). The concept was further developed by Todini (1996), with the ARNO model making use of probability distribution functions to control both moisture storage levels and drainage rates.

The model uses a kinematic wave routing scheme making use of DEM derived flow direction grids (see D8 algorithm in Chapter 4) to define flow pathways. A flow accumulation threshold defines whether a cell is treated as land or river. Catchment quickflow and baseflow response are represented using separate slow and fast routing components. This is achieved through use of two kinematic waves which are used to control the flow of water within the model. A water balance is maintained for each model grid cell controlling the production of runoff. A simple relationship between local slope and grid cell storage capacity is assumed, reducing the amount of storage on steep slopes and increasing storage in valley bottoms and areas with flat terrain.

5.2.2 Flow Routing

The G2G model utilises a flow a routing model based upon a 1-D kinematic wave, an approximation to the St Venant equations for surface flows, widely applied in the field of hydrological modelling (Lighthill and Whitham, 1955; Singh, 2001; Woolhiser and Liggett, 1967). By applying several simplifying assumptions to these equations the kinematic wave equation may be derived:

$$\frac{\partial q}{\partial t} + c\frac{\partial q}{\partial x} = cu \tag{5.1}$$

Relating river flow q and lateral inflow per unit length of river u. c is the kinematic wave celerity (velocity), t and x are time and distance along the river respectively. By approximating the derivatives an explicit discrete formulation can be made where k and n identify positions in time and space (Bell et al., 2007a):

$$q_k^n = (1 - \Theta)q_{k-1}^n + \Theta(q_{k-1}^{n-1} + u_k^n) \tag{5.2}$$

A dimensionless wave speed Θ can be calculated where $0 < \Theta < 1$ by dividing t and x into discrete intervals Δt and Δx:

$$\Theta = c\Delta t/\Delta x \tag{5.3}$$

The dimensionless wave speed provides a simple, albeit fixed, method of controlling the rate of flow within the model.

Equation (5.2) models flow for a given unit length of river q_k^n at a timestep by summing two terms. The first term $(1 - \Theta)q_{k-1}^n$ is used to calculate the proportion of flow at the river length remaining from the previous timestep q_{k-1}^n after a proportion controlled by the wave speed Θ moves downstream. The second term $\Theta(q_{k-1}^{n-1} + u_k^n)$ controls the magnitude of flow into q_k^n from lateral hill-slope flow u_k^n at the current timestep and upstream flow from the previous timestep u_k^n with magnitude controlled by the wave speed Θ.

Equation (5.2) can be further developed to provide the basis for a hydrological model that utilises a slow kinematic wave to represent the movement of soilwater and groundwater and its contribution to the baseflow component of river flow. A fast kinematic wave is used to represent movement of water over land as throughflow and overland flow. Model cells are defined as either land or river with a separate set of wave equations defined for each class. This gives rise to a system of four kinematic wave equations to model surface and subsurface flows. Return flow occurs between the slow subsurface wave and the fast surface wave.

The following model equations are used to represent overland and subsurface flows on the hill-slope as fast and slow kinematic waves:

$$\frac{\partial q_l}{\partial t} + c_l \frac{\partial q_l}{\partial x} = c_l(u_l + R_l) \tag{5.4}$$

$$\frac{\partial q_{lb}}{\partial t} + c_{lb} \frac{\partial q_{lb}}{\partial x} = c_{lb}(u_{lb} - R_{lb}) \tag{5.5}$$

where c_l and c_{lb} are the wave celerity of overland and subsurface flow, correspondingly u_l and u_{lb} are the inflows to the cell while R_l and R_{lb} are the return flows from subsurface to the surface.

Flows within cells defined as river are also calculated with a fast and slow wave using the same form, with subscripts r and rb, representing surface and subsurface flow within cells defined as river:

$$\frac{\partial q_r}{\partial t} + c_r \frac{\partial q_r}{\partial x} = c_r(u_r + R_r) \tag{5.6}$$

$$\frac{\partial q_{rb}}{\partial t} + c_{rb} \frac{\partial q_{rb}}{\partial x} = c_{rb}(u_{rb} - R_r) \tag{5.7}$$

A D8 representation of flow direction can be incorporated into the model allowing inflows to a cell to be made from upstream adjacent cells, allowing a 2D representation of flow. The slow and fast waves are maintained separately however interaction between them allows water to move from the slow wave to the fast wave. In addition model cells can be given different values of celerity allowing rivers and streams to be given a faster flowrate than the flow overland.

The four model equations are represented in the form of equation (5.2) as follows:

$$q_k^n = (1 - \Theta)_{k-1}^n + \Theta(q_{k-1}^{n-1} + u_k^n \pm R_k^n) \tag{5.8}$$

With the appropriate non-dimensional wave speed Θ calculated using equation (5.3) based upon the surface and subsurface celerities for land and river cells. In practice a single pair of slow and fast waves are maintained within the model with the wave speed Θ set to the appropriate value for cells defined as as land or river. The store of water within cells is carried out using an equivalent depth, at a given timestep a water depth in mm is assigned to the cell effectively replacing q_k^n with S_k^n.

To convert from the stored depth S_k^n to a model flowrate q_k^n the volume of water held in the cell is calculated based upon the cell area and equivalent depth. This is summed for all the timesteps forming the current day, then divided by the number of seconds (86400 s) to give the mean daily flow in m^3s^{-1}.

5.2.3 Runoff Production

The movement of water within each model cell is controlled based upon the slope of the cell, with steeper cells producing quickflow more rapidly than flat cells (Bell and Moore, 1998). This provides a simple approximation of the generation of hill-slope throughflow, as described using the straw roof analogy in Chapter 2, whereby water is more inclined to move laterally through the top layer of soil than percolate downwards when there is a steep gradient. The maximum moisture storage of the cell S_{max} is varied with the local slope using the relationship:

$$S_{max} = \left(1 - \frac{\bar{g}}{g_{max}}\right) c_{max} \tag{5.9}$$

where $\bar{g}$ is the average topographic gradient of the cell, g_{max} is maximum gradient and c_{max} is the maximum storage capacity. g_{max} and c_{max} are set globally allowing distributed cell storage to be set using only these parameters and the catchment slope.

Water enters the cell as rainfall, it can then leave through evapotranspiration, as overland throughflow contributing to the catchment quickflow response or by draining from the cell contributing to the baseflow response. Loss due to evapotranspiration E_a is determined based upon the level of moisture in store and the applied potential evaporation rate E and can be considered equivalent to actual evapotranspiration.

$$E_a = E\left\{1 - \left(\frac{S_{max} - S}{S_{max}}\right)^2\right\} \tag{5.10}$$

Drainage from the cell into the slow kinematic wave is controlled using a drainage rate constant k_d and exponent β which is set to 3.

$$d = \begin{cases} k_d S^{\beta}, & S > 0, \\ 0, & S \leq 0, \end{cases} \tag{5.11}$$

Storage of water within each cell is controlled based upon a balance of rainfall rate $p\Delta t$, evaporation rate $E_a\Delta t$ and drainage rate $d\Delta t$.

$$S = max(0, S + p\Delta t - E_a\Delta t - d\Delta t) \tag{5.12}$$

5.2.4 Probability distributed storage

The mechanism controlling contribution to baseflow has been described in the previous section, however generation of quick overland and throughflow has not yet been introduced. The formation of surface hill-slope flows uses two methods the first is based upon the local slope controlled storage limit S_{max} with saturation excess overland flow generation controlled by:

$$q = max(0, S - S_{max}) \tag{5.13}$$

where overland flow q is produced if the storage capacity of the modelled cell is exceeded.

As discussed in section 5.2.1 the model accounts for the heterogeneity of real hill-slope conditions, where the amounts of throughflow and overland flow production compared to water in held in store vary significantly within a local area (Frisbee et al., 2007). This is achieved by use of a probability distributed moisture store, controlled by parameters b and C_{max}, allowing quickflow to be produced at all levels of moisture held within a cell (Bell and Moore, 1998; Moore, 1985; Moore and Clarke, 1981; Todini, 1996; Zhao, 1977).

The distribution of slope within a catchment can be characterised by a Pareto distribution. This idea is extended and the slope within a model cell is assumed to also form a Pareto distribution. As the moisture storage used in the runoff production scheme is assumed to be related to the cell slope, it continues that the storage available within a cell can be represented as a Pareto distribution function creating variability in the generation of runoff at different levels of saturation.

The shape of the Pareto distribution is controlled by a factor b which is determined from the regionally set maximum slope value and the local cell mean slope $\bar{g}$, using:

$$b = \frac{\bar{g}}{g_{max} - \bar{g}} \tag{5.14}$$

The proportion of water that enters the cell store S is controlled by:

$$S(t) = \frac{c_{max}}{b+1}\left[1 - \left(1 - \frac{C^*(t)}{c_{max}}\right)^{b+1}\right] \tag{5.15}$$

where C^* is the critical moisture threshold above which runoff is generated. In practice C^* is calculated by rearranging the previous equation for C^*, allowing the critical threshold to be determined for a a current level of moisture held in store. The proportion of subsequent precipitation entering the cell above this threshold is added to the catchment fast response.

There is strong interdependence between parameters b and C_{max} in equation 5.15 which would make calibration challenging if they were left unfixed. By setting C_{max} as a regional value and estimating b from gradient, this issue is avoided. However, a more complete approach would use additional physical catchment descriptors to estimate C_{max} and b.

5.2.5 Snowmelt model

As large proportions of the Scottish uplands experience reasonable levels of snowfall each year, a degree-day based snowmelt model was incorporated within the G2G model with the aim of representing the effect of water storage this creates within catchments. The role of snowmelt is argued to be important for hydropower within Scotland as peak winter precipitation events consisting of a large proportion of snow will be released slowly into the catchment, preventing reservoir overspills and the capacity of run-of-river schemes from being exceeded.

This model utilises the gridded temperature dataset developed in Chapter 3 to implement a simple degree day approach (Rango and Martinec, 1995). Below a certain temperature threshold ,T_{snow}, all precipitation is assumed to fall as snow. Above another threshold, T_{rain}, all precipitation is assumed to fall as rain. Between these two thresholds a mixture of snow and rainfall is assumed and the amount of snow is determined as a fraction using:

$$S_{snow} = \frac{(\bar{T} - T_{snow})}{(T_{rain} - T_{snow})} \tag{5.16}$$

where $\bar{T}$ is the daily mean air temperature. Snow is stored as an equivalent water depth S_{snow} above the model grid square. The equivalent depth of meltwater S_{melt} in mm is controlled using the degree day snowmelt formula:

$$S_{melt} = F \times max(0, \bar{T} - T_F) \tag{5.17}$$

where F is the the degree day factor, $\bar{T}$ is daily mean temperature and T_F is a temperature threshold. This method is relatively simple and could be further refined, for example by accounting for the effect of terrain characteristics such as aspect and exposure to wind on accumulation and melt rates

5.2.6 Summary of Parameters

The G2G model uses 7 control parameters that need to be set by the user or determined through calibration (see Table 5.1) making it a relatively parsimonious model when compared to other distributed models. The use of slope to control the amount of storage in model cells allows catchment storage to be represented in a distributed by setting the regional storage value c_{max} and a value for maximum gradient g_{max}.

A suitable value for g can be determined from DEM estimates of slope and in this work has been set at 60%. Application of equation 5.14 produces a range of values for b. Typical values are illustrated in figure 5.2 and 5.3, with the Tay catchment chosen here as it features a range of upland and lowland areas. The majority of cells are assigned a value of less than 4, although the value increases significantly for cells with slopes approaching the upper limit g_{max}.

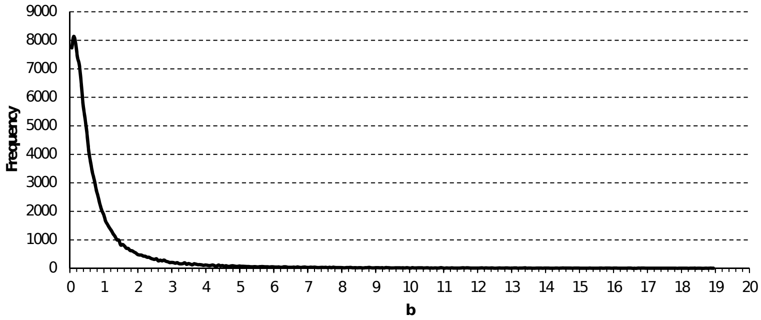


Figure 5.2: Histogram showing distribution of b within the Tay catchment

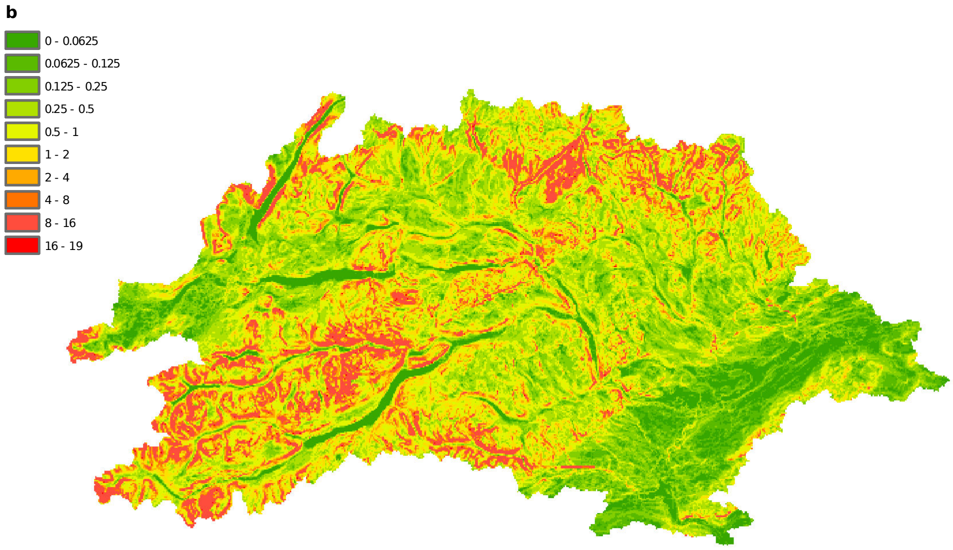


Figure 5.3: Map of b estimated from mean slope for Tay catchment

The addition of a snowmelt model adds 4 further parameters. As this significantly increases the number of parameters to be calibrated and due to a general lack of suitable data to calibrate the snowmelt model against these have been fixed based upon parameters found by Dunn and Colohan (1999).

Parameter	Symbol	Units	Typical value	Description
Surface wave speed:				
Land	c_l	ms^{-1}	0.4	Velocity of quickflow
River	c_r	ms^{-1}	0.5	
Sub-surface wave speeds:				
Land	c_{lb}	ms^{-1}	0.05	Velocity of baseflow
River	c_{rb}	ms^{-1}	0.05	
Return flow factors:				
Land	r_l	-	0.005	From subsurface to surface
River	r_r	-	0.005	
Runoff production:				
Maximum storage depth	c_{max}	mm	140	
Drainage rate	d	-	0.000005	
Pareto distribution shape	b	-	0.01 to 4	
Snowmelt Model:				
Rainfall threshold	T_{rain}	$^{\circ}$ C	1.86	
Snow threshold	T_{snow}	$^{\circ}$ C	-0.287	
Snowmelt threshold	T_F	$^{\circ}$ C	1.86	
Degree day factor	F	mm/$^{\circ}$ C / day	9	-

Table 5.1: Model control parameters with typical parameters (Bell et al., 2007a; Dunn and Colohan, 1999)

5.3 Code Implementation

The model code was developed using a combination of C++ and Python code. C++ is a relatively low level compiled language that enables creation of fast optimised code (Lischner, 2003). There are relatively few libraries available when compared to other higher level languages, however. Conversely Python is a high level interpreted language with large numbers of libraries available but with relatively poor performance (Martelli, 2003).

The mantra “Python for control, C++ for speed” formed the core of the development philosophy, extensive use was made of pre-existing software libraries to perform data I/O, preprocessing and post-processing. Model control scripts were all written in Python. The G2G model itself was entirely coded in C++, the use of Simplified Wrapper and Interface Generator (SWIG) enabled the code to be wrapped as a Python extension making the model functions callable from within the Python environment. This enabled the leverage of the flexibility and rapid development potential of Python with the performance advantage of C++ (Beazley, 1996a,b).

Model code was created using a simple object based approach. The model was created as an object 'G2G'. When the object is called within a Python script a number of 2D array data structures are created within C++. The functionality of the model consists of a number of methods that are applied to data structures, performing the different water balance and flow routines. Essentially a number of 2D arrays are created, these are then filled with the necessary GIS and meteorological data, this is then processed in place by the various model functions to minimise the creation of new arrays and copying of data.

5.3.1 Code Performance

A suitable level of performance was achieved with completion of a 1 year run for a catchment of 300 km^2 achieved in under 10 seconds. Size of catchment, chosen resolution, and length of model run, all impact performance. Runtimes at 200 m resolution are significantly longer, measured in hours and days, due to the 25-fold increase in number of model cells and a requirement to use shorter timesteps to maintain numerical stability. As run times are much shorter when 1 km spatial resolution is used all calibration approaches involving large batch runs have been carried out at this resolution.

5.3.2 Available Computational Environment

All development work has been carried out in Scientific Linux upon a Sun workstation with Intel core 2 duo processor. For application at national level a method to scale up use of the model was required. Two available architectures were considered: a Beowulf Cluster or Condor-based distributed batch processing system which utilises a pool of Sun workstations.

A Beowulf Cluster utilises standard PC hardware to enable creation of parallel processing environments (Sterling, 2002). Software designed for this sort of environment will typically use a form of message passing interface (MPI) enabling a task to be split up and spread over several processors with communication occurring between each. In terms of grid based environmental models it is typical to split the domain up into smaller sub-domains and process each of these on an individual processor (Dore et al., 2006; Peters-Lidard et al., 2007; Szunyogh et al., 2005). Alternatively a cluster environment may be used to run a single model many times using a number of processors allowing Monte Carlo approaches to be used (Beven, 2001a; Whittaker, 2004).

The use of domain-based parallelisation would allow a high resolution model of the whole country to be run as a single process split between multiple processors. While this is initially appealing the additional development and optimisation costs were considered to outweigh the potential benefits in this case. Instead catchments are effectively treated as being hydrologically independent of each other, and as each catchment model can be comfortably executed on a single processor an approach based upon this was deemed more appropriate .

Condor is a batch processing management system that is able to schedule tasks to utilise the spare capacity of pool workstations (Litzkow and Livny, 1990; Thain et al., 2005). A list of processes is submitted to the Condor queue; these are then distributed to free cores where the task is executed. If a workstation becomes busy, e.g. a local user running a process, then Condor saves the task and and places a hold status on it, when another free core becomes available then Condor will re-schedule the held task.

The use of the Condor environment enabled many thousands of model runs to be made during calibration of the 40 gauged catchments considered. Final modelling of Scotland at high resolution was achieved by splitting the country into 45 hydrometric areas and a running a model for each.

5.4 Model Calibration

There are several common methods used to calibrate hydrological models to observed gauge data. The simplest is manual calibration where the user modifies model parameters based upon analysis of the output hydrograph until a suitable set of parameters is achieved. This approach is useful as it relies upon understanding the structure of the model although a knowledge of feasible parameter values is required to start with and can be very time consuming.

Assessment of model fit can be based upon visual analysis of modelled and gauged hydrographs. It is also common to use likelihood functions of model prediction efficiency. There are various measures of model fit available each with different characteristics and it is important to note that choice of likelihood function will have a significant impact upon the resulting model parametrisation if used as part of an automated approach. This has led to the development of multi-objective techniques that allow more than one set of criteria be used as an objective function (Beldring, 2002).

The sum of squared errors also known as error variance σ_ϵ^2 or residual sum of squares (RSS) compares the modelled flow $\hat{Q}_t$ with observed flow Q_t at timesteps t using:

$$\sigma_\epsilon^2 = \frac{1}{NT}\sum_{t=1}^{NT}(Q_t - \hat{Q}_t)^2 \tag{5.18}$$

where NT is the total number of timesteps. This is a useful measure to show the amount of discrepancy between modelled and measured flow values.

Error variance is used to calculate the Nash Sutcliffe model efficiency coefficient, which is also known as the coefficient of determination or, R^2 (Nash and Sutcliffe, 1970). This is found from the error variance σ_ϵ^2 and the variance of observed flow:

$$R^2 = 1 - \frac{\sum_{t=1}^{NT}(Q_t - \hat{Q}_t)^2}{\sum_{t=1}^{NT}(Q_t - \bar{Q})^2} \tag{5.19}$$

where $\bar{Q}$ is the mean observed flow. A value of 1 indicates a perfect fit between modelled and measured data. Values below 0 occur when residual variance is greater than the variance of the observed data.

Errors between modelled and observed peak flows are usually much greater than lower stages of the flow regime, therefore these tend to have a heavier influence on the above measures than lower flows especially due to the use of the square term. To reduce the skewness in error across the flow range it is common to apply a box-cox transform to the data (Box and Cox, 1964):

$$Q_t^* = [(Q_t + 1)^\lambda - 1]/\lambda \tag{5.20}$$

where a suitable value of parameter λ is chosen, typically set to 0.3 (Vrugt, 2003).

It is useful to show the error between simulated and observed flow volumes to determine if there are problems with closing the water balance. This has been carried out here by calculating the relative error V_{err} between total simulated FDC volume and total observed FDC volume using:

$$V_{err} = \frac{\sum_{n=0}^{100}(\hat{Q}_n - Q_n)}{\sum_{n=0}^{100} Q_n} \tag{5.21}$$

where $\hat{Q}_n$ is the modelled FDC percentile and Q_n is the observed FDC percentile.

Once a likelihood measure has been chosen a parameter calibration process can then be used to optimise by minimising or maximising the measure. An exhaustive systematic search can be performed whereby a parametric sweep would be applied individually to all free parameter values. This can rapidly lead to infeasible numbers of model runs and great computational expense. Given a 7 parameter model, if a 1000 step sweep was applied systematically to each parameter then the required number of runs would be 1000^7 or 1×10^{21} runs. This number of runs could be feasible for a simple lumped model, however a distributed model with runtime in order of seconds would require great computational expense. Given this fundamental problem other methods have been developed to enable robust optimisation using a feasible number of model runs.

Monte-Carlo methods involve randomly sampling a defined parameter space and performing a model run with the sampled parameters. This is repeated as many times as is feasible to allow the model goodness of fit surface to be characterised from generated likelihood function values. There is no minimum required number of runs and the choice is largely subjective. In addition, upper and lower limits of the parameter distribution will affect results with wider limits typically requiring a greater number of runs. In an attempt to overcome these problems guided Monte-Carlo procedures may be used such as Markov Chain sampling and the METROPOLIS algorithm (Kuczera and Parent, 1998).

To further automate the calibration process, optimisation algorithms can be used. Standard approaches such as hill climbing techniques tend not to be suitable for hydrological models as the goodness of fit response surface will be multi-dimensional and the algorithm may get trapped in local minima or maxima. More sophisticated approaches such as simulated annealing and genetic algorithms which use multiple random search points with the aim of identifying a global optimum are found to be more suitable (Thyer et al., 1999).

When multiple sets of parameter values resulting from optimisation methods are plotted against model efficiency it is usual to find that good model fits can be found across the range of parameter values tested. This indicates that there is no single optimum fit. Interaction between different parameters leads to sets of parameters that may be quite different performing equally as well. This characteristic of hydrological models is termed equifinality. By accepting that there is no optimum it is necessary to understand how a model will perform for different sets of valid parameters. Methods such as GLUE may be used to characterise a models performance by using the likelihood values found for different parameter sets to create hydrograph bounds showing parameter uncertainty (Beven, 2001a; Beven and Binley, 1992).

While the GLUE approach is commonly applied in the field of hydrology it should be noted that Mantovan and Todini (2006), Stedinger et al. (2008) and Clark et al. (2011) have criticised the robustness of this approach. It is argued that the use of informal likelihood measures together with an subjective assessment of behavioural model classification lacks scientific rigour. These authors state preference for a formal Bayesian approach to allow creation of robust uncertainty estimates. Jin et al. (2010) undertook a comparison of GLUE with a formal approach and found that both produced similar estimates of parameter and simulated discharge uncertainty, although selection of the behavioural model threshold required by GLUE had significant weight on the final results. In this work the GLUE method has been employed to demonstrate equifinality across multiple parameter sets rather than as a means of producing uncertainty bounds

It is not possible to accurately measure catchment water balance using instrumentation, uncertainty in water balance measurement is introduced from rainfall, evapotranspiration and discharge measurement error (Beven, 2001b). Ideally a hydrological model should be able to reproduce catchment water balance, as measured at gauge. In practice this is often achieved using a correction factor for evapotranspiration and/or rainfall measurements. These correction factors can either be set before hand based upon experience or treated as parameters during model calibration (Lindstrom et al., 1997). While this is a suitable approach when modelling individual catchments it is more difficult when applying a hydrological model at regional level as error in the measurement of catchment area rainfall and evapotranspiration will vary across the region depending upon the terrain and the density and quality of point observations available. For this reason the use of rainfall and evapotranspiration correction factors has been avoided during this study.

5.4.1 Calibration Approach

Two methods have been employed to produce appropriate model calibrations. Firstly an automated procedure was used to produce individual catchment calibrations across a range of gauged catchments. This method utilised the shuffled complex evolutionary (SCE-UA) algorithm with upper and lower bounds set for the parameters based upon those identified by Bell et al. (2007a) and Cole and Moore (2008). This approach was used during initial model development to allow testing and to characterise the performance of the G2G model when calibrated to individual catchments.

To allow national application of the model a regional parameterisation was developed using a Monte Carlo procedure. The parameter sets obtained using SCE-UA were used to constrain the parameter space in an attempt to prevent under-sampling. 10000 parameter sets were randomly sampled from uniform distributions of parameter values and 46 catchment models were run with all sets. The best average performance across catchments within each of the three SEPA regions was used to identify a single parameter set that could be applied globally to each SEPA region. To further characterise the impact of parameter uncertainty the Generalised Likelihood Uncertainty Estimation procedure was applied to 3 catchments of varying quality of fit, this utilised the Monte Carlo runs developed previously to obtain upper and lower bounds of model performance.

Once appropriate parameter sets were identified for each SEPA region the G2G model was applied nationally at 200 m resolution. Ideally all calibration would have been carried out at this resolution however this would have been extremely computationally expensive. It was found that the parameterisation developed at 1000 m resolution was transferable to the higher resolution model.

As discussed in Chapter 2, daily average flow data is available for a large number of SEPA gauges via the National River Flow Archive (NRFA) at CEH together with coordinates and details of the recording stations (CEH, 2008a). This data forms the basis of all calibration methods performed. Calibration periods were chosen somewhat arbitrarily, but reflect when the greatest amount coverage across gauges was possible due to missing data.

5.4.2 Individual Catchment Calibration

Individual catchment calibration was performed on 46 catchments using the SCE-UA algorithm. Catchments were chosen that had available long-term time series from the National River Flow Archive. Catchment flow pathway datasets were derived using the D8 algorithm discussed in the previous chapter on a 1 km grid (see Figure 4.6 in Chapter 4). Please refer to

Table 5.5 in the previous chapter for further details of the gauging stations.

The SCE-UA algorithm developed by Duan and Gupta (1993) is a form of genetic algorithm developed specifically for automatic calibration of multi-parameter hydrological models and has been widely applied (K. Ajami et al., 2004). A uniform sample space is defined by setting upper and lower boundaries for each free parameter. Values are then randomly sampled from the parameter space to form an initial population of parameter sets. Each set is treated as an organism with the ability to procreate with other sets, the sets parameter values form its genetic make up. By evaluating the performance of each set and computing the goodness of fit of simulated results compared to observations the fitness of the individual set is recorded. Performing evolution on the sets leads to progression towards an optimally fit parameter set. Evolution is performed by splitting the initial population into sub-samples, or complexes. In each complex, different combinations of sets are assessed using a downhill simplex procedure, with new combinations of sets considered the offspring of previous sets. The probability that an individual set will take part in reproduction is proportional to its measured fitness, in this way older sets of poorer fitness are replaced by younger sets of increased fitness. Additional mutation can occur whereby random parameter values are introduced to sets. The complexes are regularly shuffled to increase the probability of sets with high fitness levels breeding. The use of the shuffling approach enables global information to be shared between the sub-populations and prevents the search from becoming trapped in local minima.

The gauged catchments were calibrated using data from the year 2007. Nash Sutcliffe was used as the objective function. Bounds for the parameter space were selected based upon those presented in Bell et al. (2007a) and Cole and Moore (2008), as shown in Table 5.2. A Python script was used to implement SCE-UA and automatically run models for the algorithm specified parameters. Each model run produced a set of simulated data which was compared to observations for the period and the Nash Sutcliffe score computed. The Nash Sutcliffe score was then returned to the algorithm to develop the next set of trial parameters. The algorithm was configured to conclude when improvement in R^2 did not occur over 10 generations.

Parameter Space Bounds								
	c_{max}	c_r	c_l	c_{rb}	c_{lb}	r	r_r	k_d
Lower	40	0.1	0.1	0.001	0.05	0.001	0.001	1×10^{-8}
Upper	200	1.5	1.5	0.1	0.1	0.1	0.1	1×10^{-5}

Table 5.2: Bounds used to limit search performed by SCE-UA algorithm

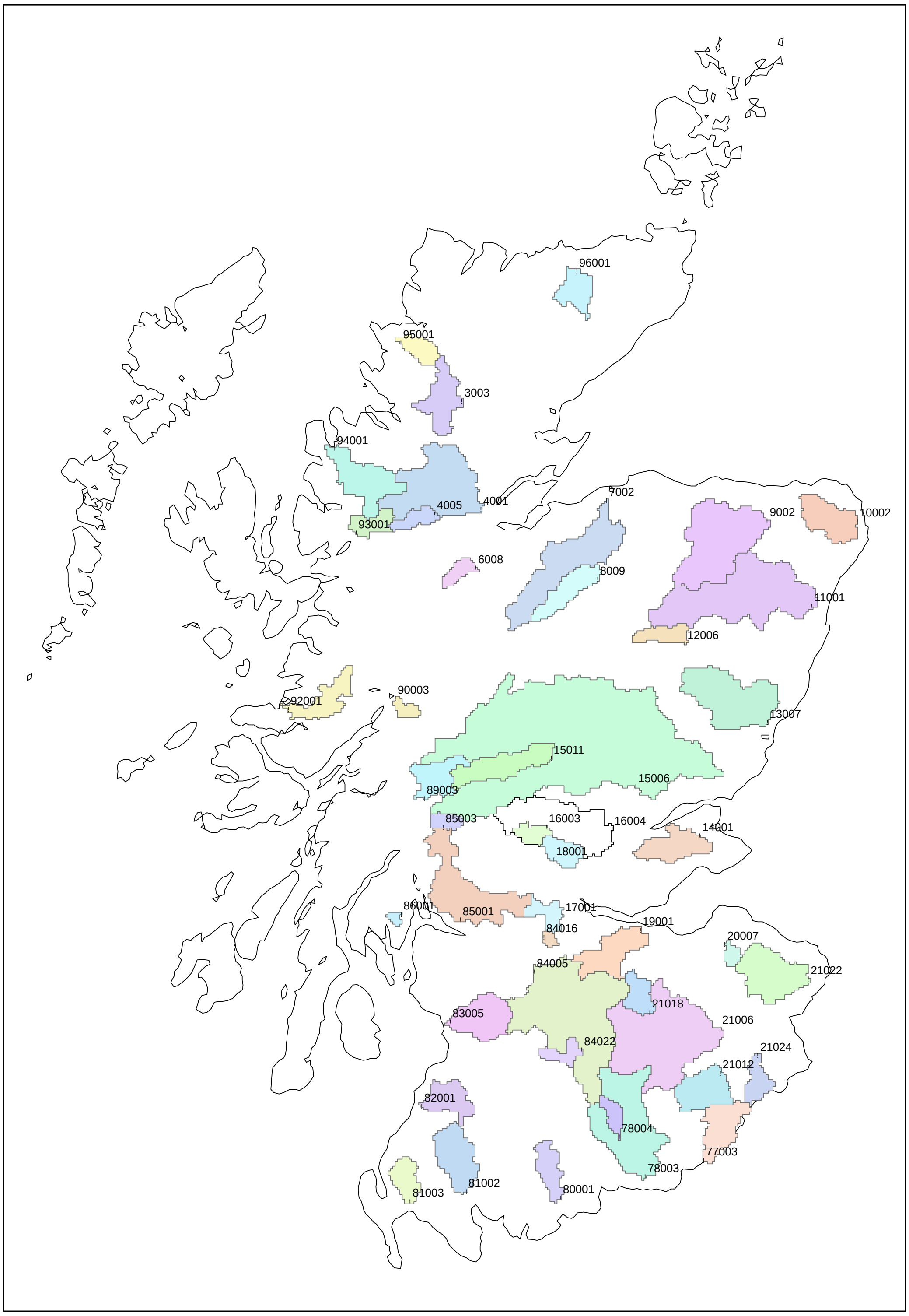


Figure 5.4: Gauged catchments used for calibration

The SCE-UA algorithm generally reached a final parameter set after approximately 2000 model runs, the results of which are presented as flow duration curves in Figures 5.5 and 5.6. There is a range of goodness of fit observed across catchments. The best performing catchments in terms of R^2 score: Ewe at Poolewe (94001), Enrick at Mill of Tore (6008) and Annan at Brydekirk (78003) are relatively small catchments located in hilly terrain. Larger catchments such as the Tay at Ballathie (15006) also show good performance. A number of catchments produce poor results in terms of reproduction of the FDC, water balance and R^2. Catchments Connon at Moy Bridge (4001), Eden at Kemback (14001), Lyon at Comrie Bridge (15011), Carron at Headswood (17001) and Leven at Linnbrane (85001) have flow regimes significantly altered by hydropower schemes, abstraction or public water supply, which explains the difficulty in achieving a good model fit. Catchments Ugie at Inverugie (10002) and Don at Parkhill (11001) have entries in the NRFA stating that the measurement gauges have a complex rating history suggesting that there may be inaccuracies in the river gauge data. Catchment Allan Water at Kinbuck (18001) has a very small catchment area, making it susceptible to error in the modelled flow pathways at 1 km^2 resolution. Other catchments such as Luggie Water at Condorrat (84016) and Inver at Little Assynt (95001) show poor performance for no easily explicable reason.

For the most part the model performs well, reproducing the FDCs with reasonable accuracy and giving an average R^2 score of 0.58. There are clearly errors introduced by failure to adequately close the water balance with a mean water balance error across all catchments of -10%, it was initially thought that the likely cause of this error was underestimation of precipitation at higher elevations. It was found that the drainage parameter k_d was receiving values that were causing more water to enter the slow model response than could be returned to the surface fast response. As such, a proportion of catchment water balance tended to exit the model before being accounted for as discharge. Based upon visual inspection of the FDCs the fit tends to be best when the R^2 score is best, however, even catchments with lower R^2 scores can achieve a reasonable FDC fit. This raises the question about the overall suitability of using R^2 as a likelihood function for this modelling application. Clearly the emphasis on reproducing correct timing of modelled flows is less important when producing an overall statistical distribution such as the FDC. A likelihood function that is less concerned with reproducing timing of events would more appropriate (Lane, 2007). However, as one of the stated aims of this work is to generate time series data for wider application of the model, R^2 was deemed appropriate.

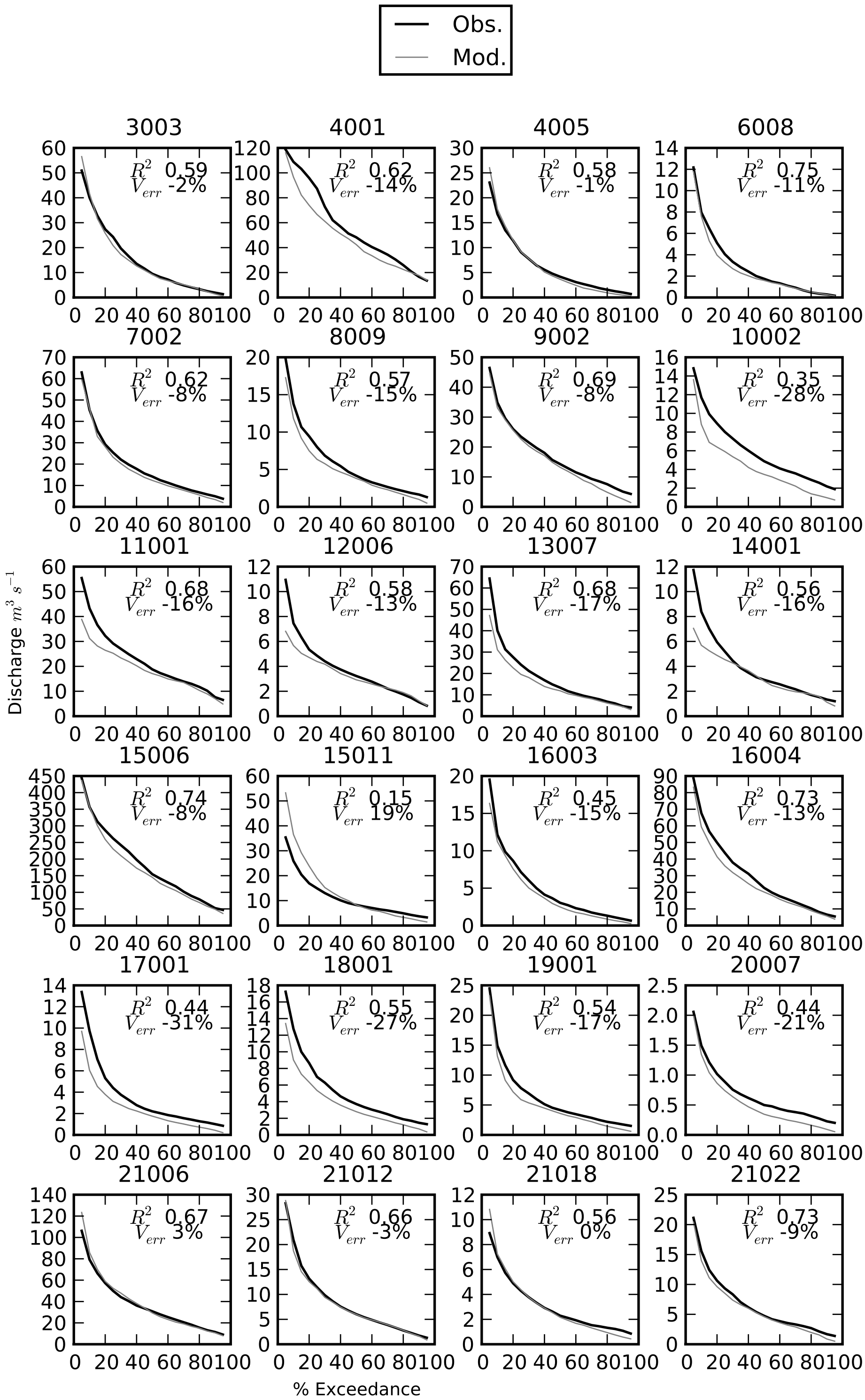


Figure 5.5: Flow Duration Curves for calibrated catchments

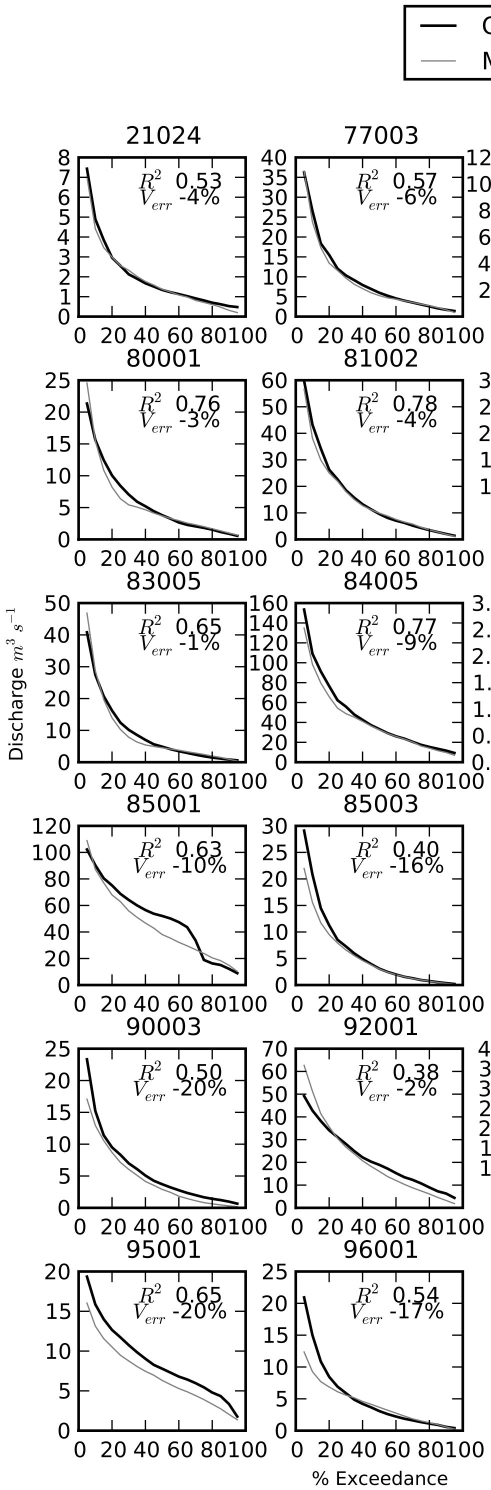


Figure 5.6: Flow Duration Curves for calibrated catchments

5.4.3 Regional Calibration

For national application, efforts were made to develop a global model parameterisation, a single parameter set that would allow model predictions to be made in all ungauged catchments. Complex regionalisation approaches can be used to allow application of parameter sets from gauged catchments to nearby catchments with similar hydrology and geography based upon relationships between parameter values and catchment descriptors (Holmes et al., 2002; Seibert, 1999; Wagener and Wheater, 2006). In addition due to the chosen distributed computational approach it was not possible to use an algorithm such as SCE-AU to calibrate all the models as a set using a single global likelihood function.

A simple approach has been used in this instance using a Monte Carlo method with a common set of random parameters developed from uniform distributions between the bounds specified in Table 5.3. It was found that increasing the return flow between the subsurface and surface for river cells using parameter r_r prevented the loss of water from the catchment as subsurface flow, reducing the negative water balance errors experienced during the SCE-AU procedure. The range of r_r used during the Monte Carlo procedure was modified to reflect this and increased to a value greater than suggested in Table 5.2.

The G2G model was applied to the 46 gauged catchments and 10000 Monte Carlo runs were performed on each for the period 1997-1999. 10000 parameter sets were defined and used for each catchment. The performance of each parameter set was assessed across all catchments by calculating the mean value of each catchment likelihood function. This allowed a parameter set with reasonable performance across all catchments to be selected. A simple regionalisation was performed by selecting 3 parameter sets one for each of the SEPA regions, North, West and East. This gave some consideration to the differences in hydrology between the different regions, additionally it was possible to select a parameter set that gave a better average performance compared to the single global national case.

	Parameter Space Bounds							
	c_{max}	c_r	c_l	c_{rb}	c_{lb}	r	r_r	k_d
Lower	50	0.5	0.5	0.01	0.01	0.01	0.01	1×10^{-7}
Upper	200	1.5	1.5	0.2	0.2	0.2	0.99	1×10^{-5}

Table 5.3: Bounds used to define uniform parameter distributions for Monte Carlo method

As discussed previously R^2 is perhaps not the best likelihood measure to use when attempting to recreate FDCs, as timing errors impact R^2 values but have less influence on FDC accuracy.

To investigate this an additional likelihood function was trialled based upon the sum of square residuals between the modelled and observed flow duration curves calculated at the end of each model run. To reduce the relative weight of higher magnitude flows during calibration a box-cox transform was applied to the flow data. While there were small differences between the modelled results it was found that the modified sum square error method offered little benefit and it was decided to retain R^2 as the likelihood function as this allows easier comparison with other work. Mean model R^2 of 0.56 was achieved for SEPA North and East, while an average R^2 of 0.51 was achieved for SEPA West. The parameter sets developed from this procedure are detailed in Table 5.4 together with parameters from the literature for comparison.

	Parameter Values							
	c_{max}	c_r	c_l	c_{rb}	c_{lb}	r	r_r	k_d
SEPA North	194	1.5	1.1	0.15	0.14	0.096	0.43	2×10^{-7}
SEPA East	200	1.18	1	0.09	0.06	0.09	0.18	1×10^{-7}
SEPA West	162	1.34	1.1	0.14	0.13	0.173	0.81	1×10^{-7}
Cole and Moore (2008)	40	1.5	0.07	0.5	0.05	0.05	0.05	1.5×10^{-6}
Bell et al. (2007a)	140	0.5	0.4	0.05	0.05	0.005	0.005	5×10^{-5}

Table 5.4: Final model calibration for each SEPA region

The selected parameter sets are similar to those applied in other studies. The values selected for r and r_r are notably different with subsurface flow returning to the surface much more rapidly. Correspondingly the drainage parameter k_d is lower reducing the rate that water enters the subsurface routing scheme. The parameter sets vary significantly by SEPA area, with the small steep catchments of the West given lower storage volumes, faster wave speeds and more rapid surface return rates than SEPA east with greater number of large catchments and lowland characteristics.

Validation of the identified parameter sets was undertaken by comparing model performance to gauge data outwith the calibration period (refer to Table 5.5 for calculated NS values). Although a range of performance was found, there was, however, broad agreement with the NS values identified during the calibration process.

5.5 Application of Model at Higher Resolution

The final modelled flows for use with the hydropower search method were completed at 200 m resolution for each hydrometric area (see Figure 5.8). One major assumption was that the regional calibrations developed in the previous section would hold at the higher resolution. Figure 5.7 provides an example of a single day's model output, showing the daily mean flow for all surface land and river cells. To minimise storage requirements only flows at river cells were recorded.

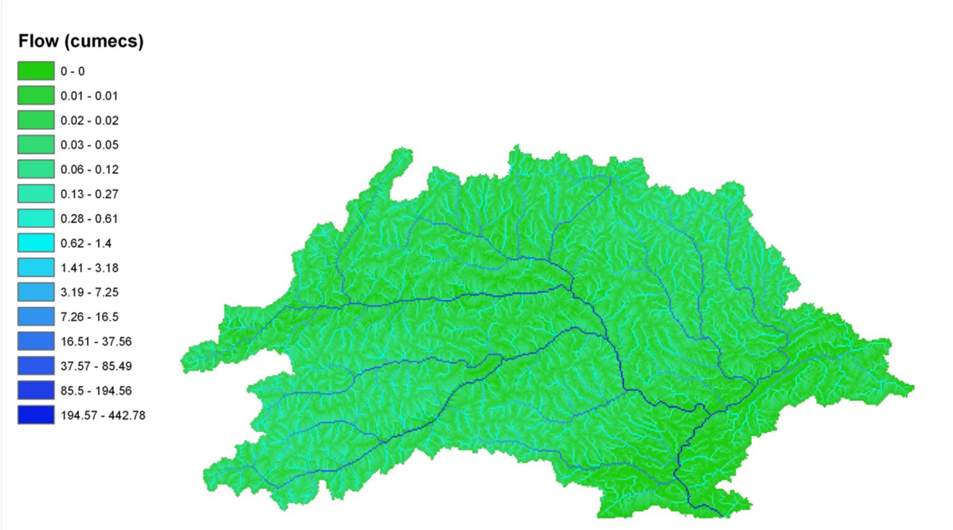


Figure 5.7: Tay hydrometric area at 200 m resolution

The data was validated using the same set of gauging stations used during calibration. Observed and flow duration curves were calculated using only data from periods with available gauge data. The resulting flow duration curves are compared to those produced from gauging stations in Figure 5.9 and Figure 5.10 together with R^2 and the water volume err V_{err}.

The modelled FDCs are generally representative of those calculated from gauge data with a range of accuracy shown across all catchments. Water volume error varies from 0% to 21% for 21022 (Lyon at Comrie Bridge, 15011, has substantial volumes transferred into another catchment as part of the Glen Lyon hydropower scheme) with over and under predictions found. A range of R^2 values are produced showing model performance ranging from good (0.75 for 78003) to poor (-0.27 for 92001) with a median value of 0.47 (excluding gauges Glen Lyon at Comrie Bridge and Leven at Linnbrane, 85001, where flow regimes are heavily modified). This gives similar levels of accuracy to Bell et al. (2007a). The underlying time series used to produce these plots is presented in Appendix A.

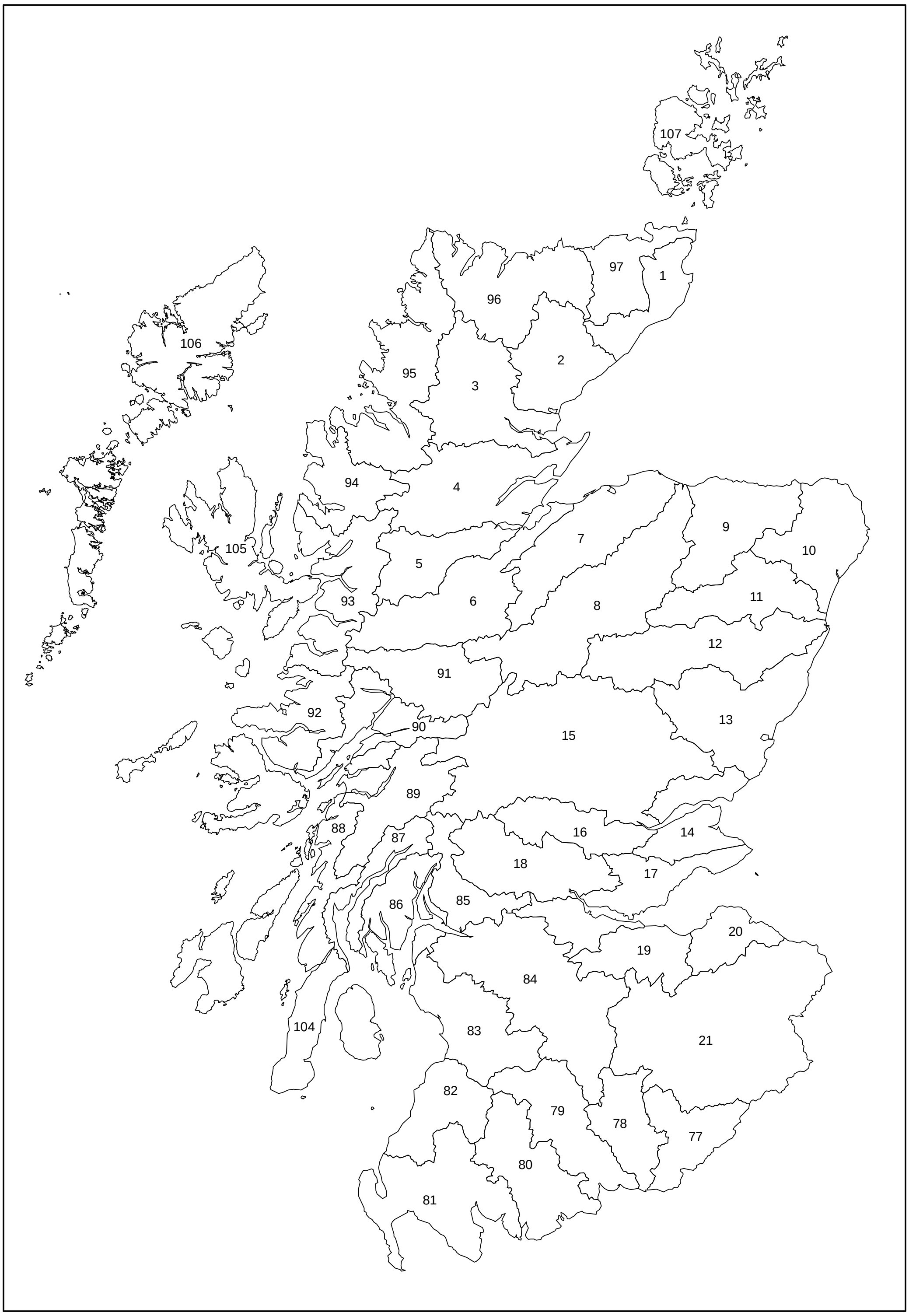


Figure 5.8: Hydrometric areas

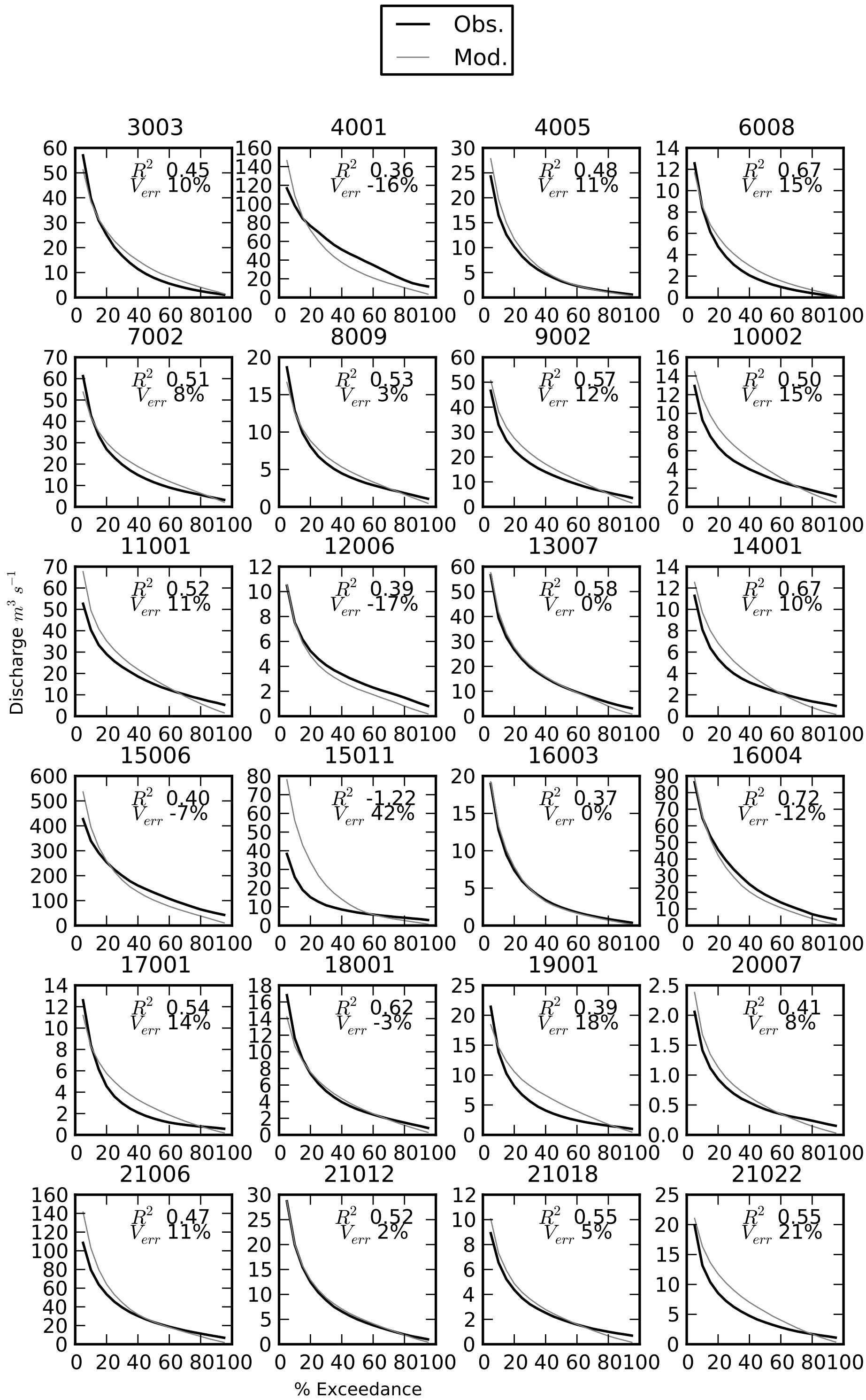


Figure 5.9: Flow Duration Curves produced from 200 m validation run

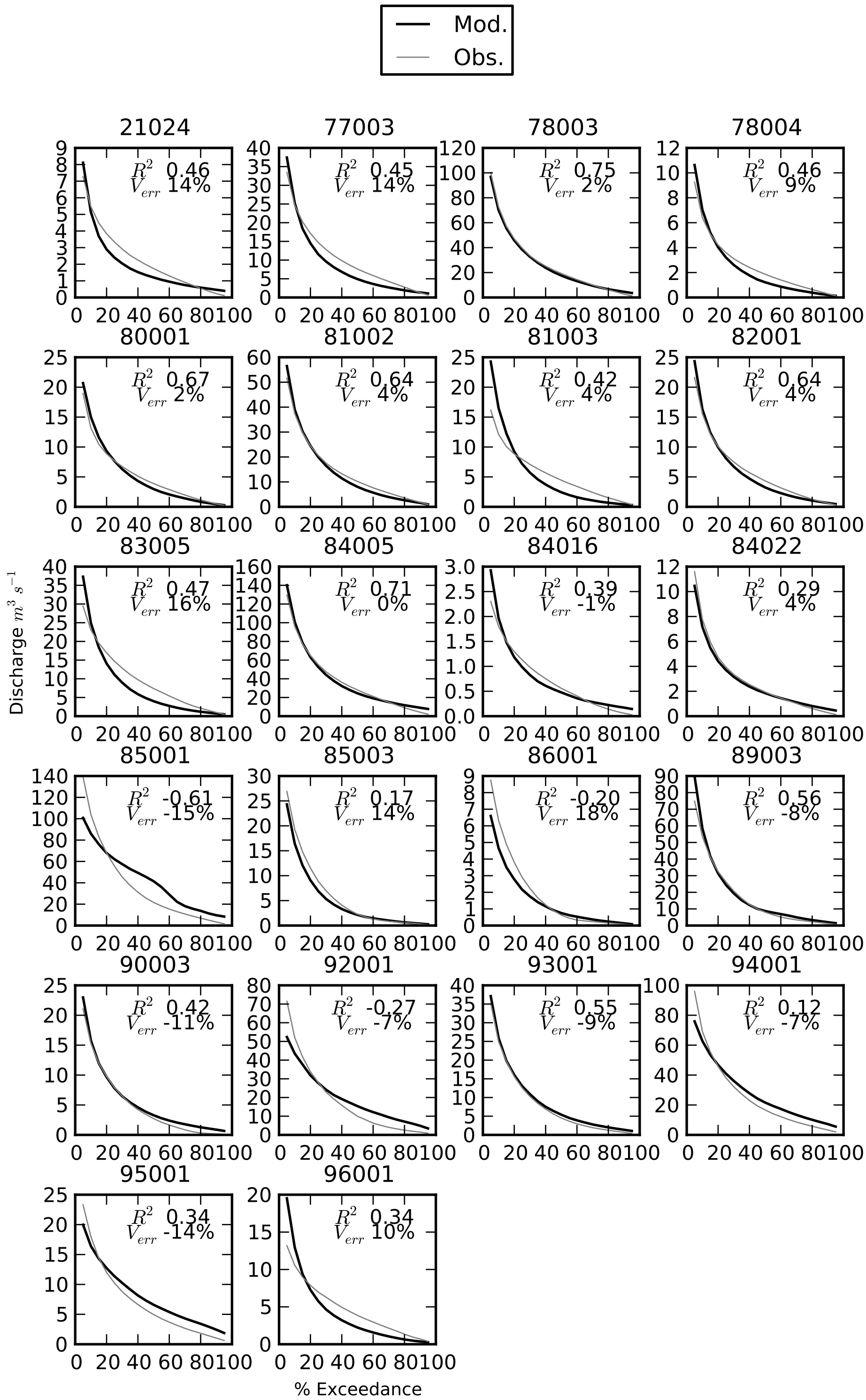


Figure 5.10: Flow Duration Curves produced from 200 m validation run

Gauge Number	River	Location	1961-1962	1971-1972	1981-1982	1991-1992	2001-2002
3003	Oykel	Easter Turnaig	-	-	0.43	0.42	0.40
4001	Conon	Moy Bridge	-0.46	-	0.44	0.34	0.43
4005	Meig	Glenmeannie	-	-	-	0.40	0.48
6008	Enrick	Mill of Tore	-	-	0.64	0.65	0.72
7002	Findhorn	Forres	0.65	0.60	0.45	0.54	0.48
8009	Dulnain	Balnaan Bridge	0.69	0.60	0.46	0.45	0.57
9002	Deveron	Muiresk	0.38	0.56	0.53	0.44	0.63
10002	Ugie	Inverugie	-	0.40	0.48	0.42	0.44
11001	Don	Parkhill	-	0.07	0.12	-	0.56
12006	Gairn	Invergairn	-	-	0.39	0.06	0.35
13007	North Esk	Logie Mill	-	-	0.50	0.55	0.61
14001	Eden	Kemback	-	0.52	0.52	0.80	0.72
15006	Tay	Ballathie	0.21	0.13	0.29	0.40	0.50
15011	Lyon	Comrie Bridge	-0.96	-0.71	-1.68	-2.13	-1.53
16003	Ruchill W	Cultybraggan	-	0.28	0.18	0.10	0.58
16004	Earn	Forteviot Bridge	-	-	0.65	0.66	0.73
17001	Carron	Headswood	-	0.41	0.39	0.41	0.45
18001	Allan Water	Kinbuck	0.55	0.48	0.52	0.58	0.70
19001	Almond	Craigiehall	0.25	0.38	0.42	0.45	0.29
20007	Gifford W	Lennoxlove	-	-	0.59	0.60	0.39
21006	Tweed	Boleside	-	0.26	0.37	0.56	0.29
21012	Teviot	Hawick	-	0.52	0.48	0.65	0.51
21018	Lyne Water	Lyne Station	-	0.27	0.46	0.69	0.18
21022	Whiteadde	Hutton Castle	-	0.62	0.46	0.69	0.47
21024	Jed Water	Jedburgh	-	0.32	0.34	0.59	0.40
77003	Liddel Water	Rowanburnfoot	-	-	0.41	0.50	0.45
78003	Annan	Brydekirk	-	0.69	0.67	0.81	0.80
78004	Kinnel Water	Redhall	-	0.35	0.35	0.46	0.53
80001	Urr	Dalbeattie	-	0.73	0.58	0.51	0.76
81002	Cree	Newton Stewart	-	0.48	0.63	0.59	0.67
81003	Luce	Airyhemming	-	0.19	0.39	0.38	0.46
82001	Girvan	Robstone	-	0.58	0.61	0.55	0.56
83005	Irvine	Shewalton	-	-	0.35	0.46	0.46
84005	Clyde	Blairston	0.60	0.64	0.65	0.79	0.73
84016	Luggie Water	Condorrat	-	0.28	0.29	0.25	0.28
84022	Duneaton	Maidencots	-	0.42	0.16	0.24	0.26
85001	Leven	Linnbrane	-	-1.37	-0.57	-1.00	-0.25
85003	Falloch	Glen Falloch	-	-0.06	0.21	-0.01	0.25
86001	Little Ea	Dalinlongart	-	-0.25	-0.07	-0.34	-
89003	Orchy	Glen Orchy	-	-	0.62	0.49	0.56
90003	Nevis	Claggan	-	-	-	0.41	0.23
92001	Shiel	Shielfoot	-	-	-	-	-0.59
93001	Carron	New Kelso	-	-	0.59	0.53	0.41
94001	Ewe	Poolewe	-	-1.32	0.29	-0.37	-0.10
95001	Inver	Little Assynt	-	-	0.61	-0.05	0.4
96001	Halladale	Halladale	-	-	0.40	0.35	0.32

Table 5.5: Nash Sutcliffe values produced for a range of 2 year simulation periods out with the 1997-1999 calibration period

5.6 Generalised Uncertainty Estimation

The use of the Monte Carlo procedure to develop the regionalised parameter also allows further characterisation of model parameter uncertainty using the Generalised Likelihood Uncertainty Estimation (GLUE) method.

The GLUE methodology has been implemented using the following steps:

1. The 10,000 parameter sets developed for the regionalisation procedure were used to perform model runs.
2. The likelihood function associated with each parameter set was calculated.
3. A minimum cut-off threshold of $R^2 > 0.5$ was used to remove non-behavioural catchments.
4. The values of R^2 found for each parameter set were normalised so that they cumulatively summed to 1.
5. At each time step the flow values for each of the behavioural catchments was assigned a probability value using the normalised likelihood values.
6. For each time-step a cumulative density function (CDF) was created by ranking the flow and cumulating the probability values.
7. Upper and lower prediction bounds were then produced for confidence intervals of 5 percent and 95 percent.

This method was applied to catchment 21024 which achieved a mid-ranking model fit. The parameter values forming the sets against R^2 are shown as a series of dotty plots in Figure 5.11. This catchment model is shown to be less sensitive to surface and sub-surface wave speeds and maximum moisture storage levels while return flow and drainage parameters are shown to be the most sensitive. The sensitivity of performance can be inferred by examining the extent to which the Nash Sutcliffe score changes as parameter values increase from left to right.

The CDFs calculated at each time step are used to create upper and lower bounds (see Figure 5.12) at 5% and 95%, effectively showing the impact of different reasonable parameters will have upon the predicted hydrograph. Uncertainty is clearly greatest during periods of high

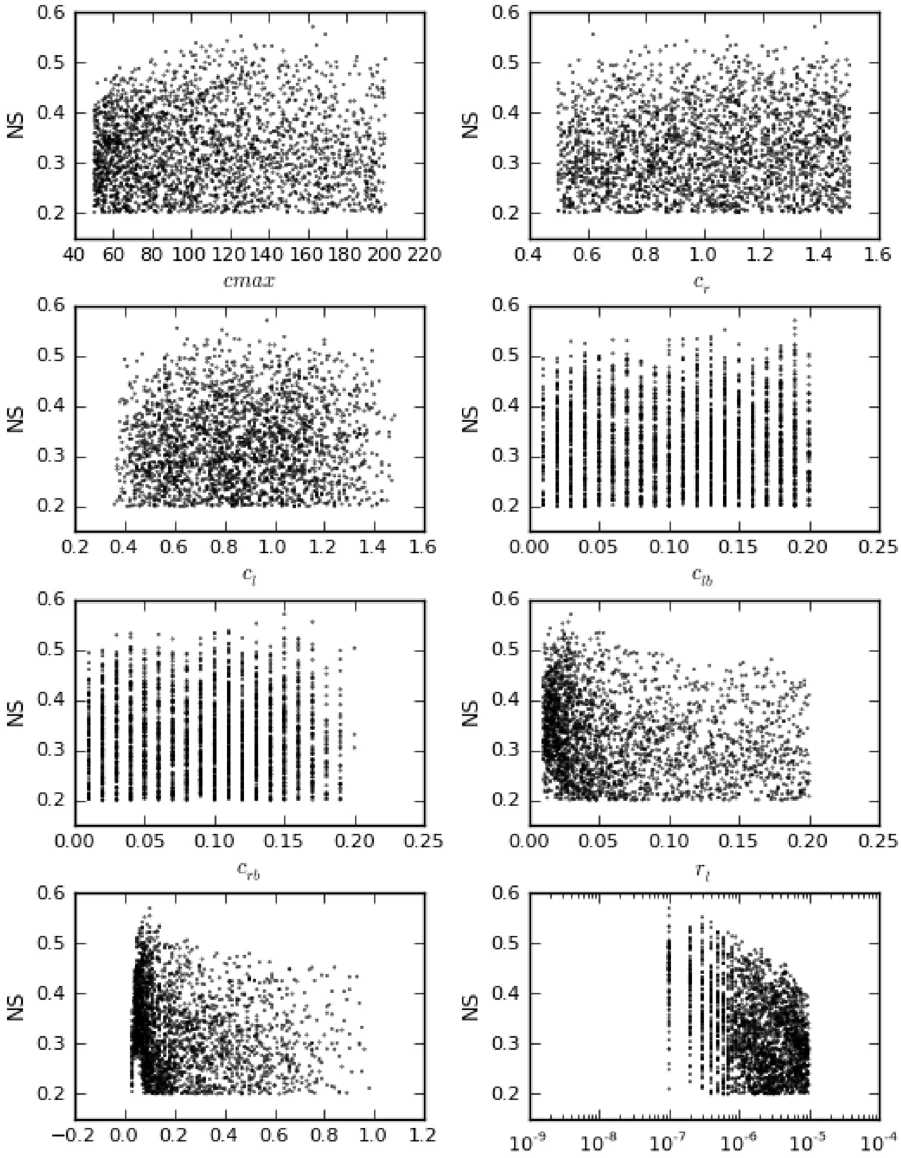


Figure 5.11: Dotty plots of Nash Sutcliffe score vs parameter values for 1997

flows. The model can be seen to under predict the low flow periods, even with the uncertainty bounds indicating that the models representation of baseflow is inadequate. This illustrates that a less than ideal model fit does not indicate failure in the calibration process, but suggests that there are problems with the underlying model structure or quality of the input data.

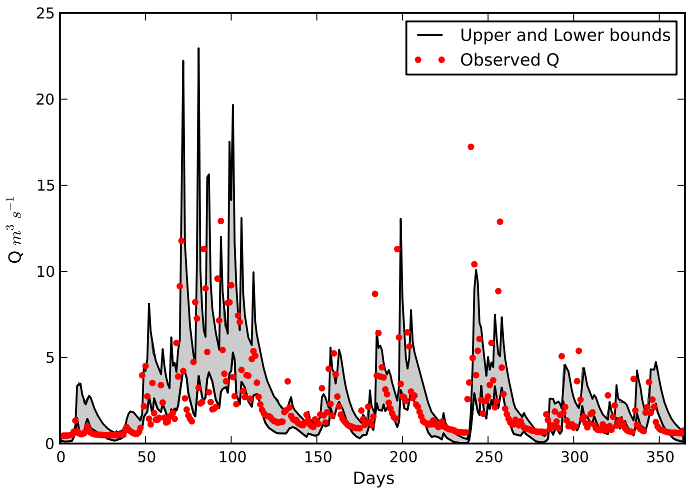


Figure 5.12: Upper and lower prediction bounds representing confidence intervals of 5% and 95% compared with observed Q for 1997

5.7 Chapter Summary

This chapter describes the development of an implementation of the G2G model using slow and fast kinematic waves to present surface and sub-surface flows and a run-off production scheme controlled by local gradient. Models of individual gauged catchments were independently optimised using the SCE-UA algorithm to characterise model performance and define appropriate bounds for use with a Monte Carlo procedure. A simple regionalisation was performed using a Monte Carlo procedure with common parameter sets which were applied at each catchment. The best overall parameter set was then chosen based upon the highest achieved mean R^2 value across all catchments. The model was then run at a higher 200 m resolution to produce final flow datasets for each hydrometric area for the period 1961 to 2005.

Validation was performed against a number of gauges to show the performance of the model which was found to produce reasonable estimated FDCs. The confidence in model predictions at ungauged locations is difficult to determine. In terms of using FDCs to assess sites for hydropower potential the overall volume error is considered key as this will determine energy yield estimates and hence project economics. The volume error found between simulated and observed FDCs was found to typically have a magnitude between 10-20%, it is reasonable to assume that this is the level of error associated with simulated FDCs in ungauged catchments.

6
Integrated Hydropower Search Database

6.1 Introduction

This chapter focuses upon the development of a method to identify economic Scottish hydro sites utilising the modelled flow time series described in the previous chapter and the addressed vector stream dataset described in Chapter 4.

A database has been created to store all relevant data, which is accessed by a search algorithm used to identify the suitability for hydropower production at geographical locations. The search algorithm is primarily written in Python with a local site optimisation and costing method coded in fast C++ code to allow large number of trials of different sizes of scheme and penstock size to be made at each location.

Suitability of sites is determined by the project economics, based upon a financial assessment of the projects potential revenues from electricity sales compared to development and maintenance costs. As design details of hydro sites are highly site specific, the most economically efficient locations can only be considered by performing a certain amount of local site optimisation to determine the size and cost of components and energy production potential for a given location. Both run-of-river and impoundment sites have been assessed.

For run-of-river schemes analysis of energy production is performed by using the FDC as a measure of available flow while impoundments use a representative amount of flow time series. The availability of flow time series makes it possible to then produce time series of power output from identified locations which can be aggregated to show the variability of potential national output.

6.2 Database Design

Ideally the development of the database and search algorithm would have been carried out within a GIS environment such as ArcGIS. Given the level of resolution required to conduct a comprehensive search, the extensive time series of river flows and the need to perform iterative searches through data this was not possible (see Chapter 2 for further discussion). To enable the goals to be met an alternative open-source solution was sought that would allow searches to be performed on individual hydrometric areas using multiple Linux workstations.

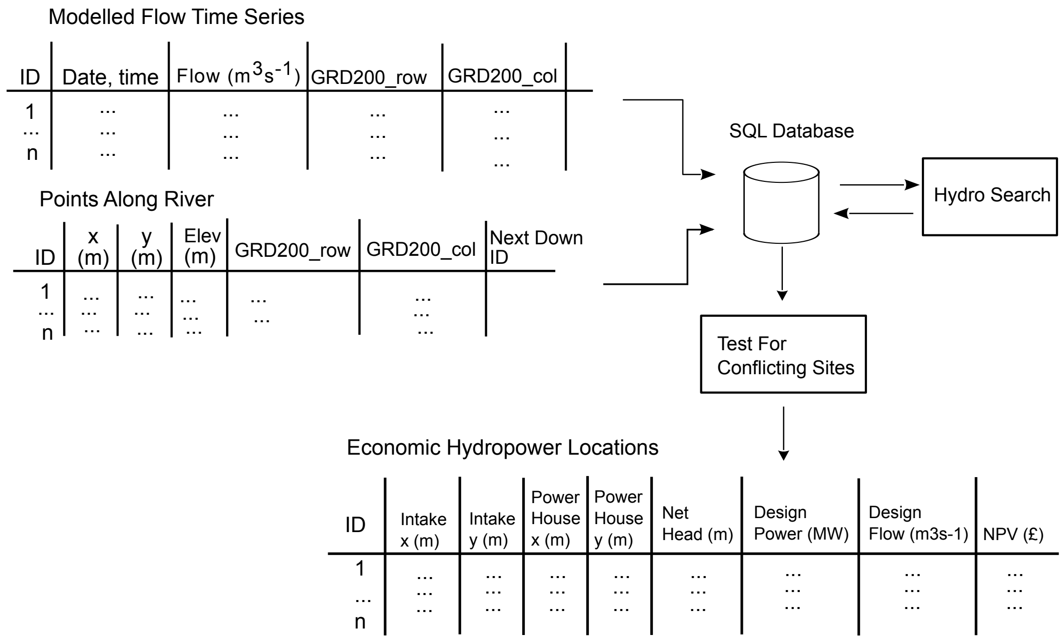


Figure 6.1: Overview of database design

PostgresSQL was identified as a suitable platform for implementing a solution (Leone et al., 2006; The PostgreSQL Global Development Group, 2010). PostgresSQL is an open source relational database compliant with Standard Query Language (SQL). The Database enables tables of data to be created that can be processed and sorted using standard database techniques. A table containing addressed river locations was created with characteristics of rivers at points along each reach. Another table of flow data was created for each hydrometric area and spatially linked to the river locations using the parameters GRD200_row and GRD200_col which define the location of points on an Eastings and Northings basis. This allows the search code to access the necessary river characteristics and flow data at points along each reach. Figure 6.1 provides an overview of the process.

A separate database was created for each hydrometric area (HA) on the local drive of a Sun

Linux workstation. A script was created to allow databases to be created as and when required; this allowed a number of machines to be used to process HAs in batches rather than using too much of the available computing resource.

Identified sites are stored in a database table of potential sites along with key design and financial criteria, these are then assessed for conflicts. Finally a table of economically viable hydropower locations is produced that can be used for further analysis and production of resource maps using GIS software.

6.2.1 Database Integration

The PostgreSQL database was integrated into the hydro search program using an SQL python library Psycopg, which allows SQL commands to be transmitted from Python to an SQL database and the resulting search data returned allowing the SQL database to act as a data storage backend for the Python program (Varrazzo, 2010). This is in many way similar to the functionality offered by ArcGIS, albeit with more power and flexibility, which stores vector data in a Microsoft Jet database backend and enables data processing using spatial queries to be performed.

6.2.2 River Data

River addressing was carried out using the ArcGIS ArcHyro package (Maidment, 2002). Hydro networks were created based upon simplified OS river lines as discussed in Chapter 4 and populated with 'Hydro ID' addresses allowing an iterative search along river networks to be performed.

Points were added at 10 m intervals to the river lines using Hawth's Tools 'Lines to Point' tool in ArcGIS. These points were then populated with elevation data from 10 m OS Profile DEM to enable head calculations. To enable flows to be assigned to the points data, column and row addresses were added allowing the grid based 200 m flow data to be joined with the points' data. Essentially this allows an SQL search of the flow table to be performed using the references held within the 10 m river points table.

The river points are held in the database as a table. Each river point is stored as a record within the the table with the key attributes of that river point held in defined fields (see Table 6.1 for description). The river data can be accessed from the database using an SQL query such as the

Field	Description
HydroID	Enables hydrological network tracing
StepID	Number of 10 m increments from top of reach
NextdownID	Identifies the next downstream river feature
x	British National Grid Easting
y	British National Grid Northing
Elevation	Elevation above sea level
fac10	Flow accumulation derived from 10 m DEM
fac200	Flow accumulation derived from 200 m G2G model DEM
GRD200_row	Used to locate 200 m G2G model output data
GRD200_col	Used to locate 200 m G2G model output data
GRD10_row	Used to locate impoundment details
GRD10_col	Used to locate impoundment details
Road_distance	Distance in m to nearest road
Line_distance	Distance in m to nearest 33 kV line
Substation_distance	Distance in m to nearest primary substation
tested	Set to 1 if point has already been assessed

Table 6.1: Parameters stored for each river point

following:

```
SELECT elevation, nextdownID,x,y,fac10,fac200,GRD200_row,GRD200_col,tested
WHERE hydroid = 820 AND stepID = 1
```

The location of the river can then be traced by incrementing the ‘StepID’ value and running another query. Once the ‘StepID’ is incremented beyond the maximum value for the river reach the SQL search will return a null value. This is used to detect the end of the river section. The search moves onto the next downstream reach by executing a query with the ‘NextdownID’ value for ‘HydroID’ and a ‘StepID’ value of 1.

The furthest downstream points occur when the river network reaches the sea. This is indicated by a value of -1 for ‘NextdownID’ hydroid. Once the end of a reach with ‘NextdownID’ of -1 is found the search starts again at a different part of the network working its way downstream.

To prevent repeat searching of the downstream sections a value of 1 is assigned to the river point value searched after it has been retrieved from the database. If a point that has already been searched is returned from the database the search of the particular river reach is halted and the search begins again at a different reach. This process is repeated until the value of ‘HydroID’ entered into the SQL query has been decremented to zero.

Field	Description
Date	Date in Julian days
Flow	Average daily flow value in m^3s^{-1}
GRID200_row	Spatial locator in x dimension based upon 200 m model grid row
GRID200_col	Spatial locator in y dimension based upon 200 m model grid columns

Table 6.2: Structure of river flows database list

6.2.3 Flow Data

The daily average flow data produced using the G2G model for each HA is held for all modelled days from 1961 to 2005 as a table of values using the structure shown each modelled 200 m cell using the structure shown in Table 6.2.

The row and column identifiers are assigned from the 200 m grid corresponding to the modelled flow matrix indices at locations designated as 'stream'. When a river point is retrieved using an SQL query like the one presented in the previous section a subsequent query can be made for flow data using the row and column identifier. This returns the modelled flow at that particular river location (in GIS parlance this is known as a spatial join). Flow data is returned from the database and stored in a Python list which can then be used by the hydro search function. The advantage of storing the flow data only at river points of interest is that the data storage requirements are greatly reduced when compared to the alternative of storing a 200 m grid for every modelled day.

6.2.4 Optimisation

To enable faster database access the river points and river flows tables were split into multiple tables based upon geographical location. Each hydrometric area was split into 10 km cells, with a river points and flows table created for each cell. When accessing river points using an SQL query the correct cell and table are located based upon Easting and Northing of the point. As the database makes use of large tables it was found to be crucial that the table was suitably indexed to minimise the search time needed by the database.

Initially it was planned to perform the hydropower search by investigating each 10 m spaced river point. To improve performance, however, it was found that using a stride of 5 was more practical, i.e., every 5th river point is interrogated. This reduces the resolution of the search to 50 m increments, however, as each upstream point is tested against a number of downstream points the reduction of tests is effectively n^2. This change increases search speed by up to 25 times. The impact upon location of small hydro sites will be minimal as very few will have penstock lengths of less than 500 m. If the search method was re-conceived to investigate micro-hydro sites then the stride could be reduced to 1 m, however, extended run times would have to be planned for or the area of study reduced. A concern related to increasing the stride was that river reaches less than 50 m in length would cause the algorithm to fail. In anticipation of this the search is always started at the first river point of the reach; where StepID is incremented by 5 and no results are returned for the reach, the NextdownID will be available to allow the next down reach to to be identified.

6.3 Search Methodology

The search algorithm was initially conceived for run-of-river schemes but was later extended to handle impoundments. This section is intended to relate specifically to run-of-river hydro but much of the contents apply directly to the impoundment search method outlines in section 6.7.

The search algorithm moves iteratively from the top of a river reach downstream until the end of the reach. At points along the river a virtual penstock with powerhouse is extended downstream and trials are performed of different penstock width and design flow until an economically optimal solution is found. If the net present value of the location over a 25 year project life is positive then the scheme is stored in a solutions table. Once the search is complete, conflicting solutions (intake of scheme B is below intake of scheme A for example) are compared and the solutions with lower NPV value are rejected. Figures 6.2 and 6.3 describe the process that is used by the search algorithm: Figure 6.2 focuses upon the top level search method while Figure 6.3 describes the local site optimisation.

6.3.1 Assumptions and Limitations

Hydropower projects are inherently site specific and are effectively crafted to fit local hydrology and topology using a significant amount of engineering judgement and specific survey data. To enable an automated search and optimisation method to be developed it is necessary to simplify certain aspects of the problem to allow the problem to be solvable. The following list provides an overview of the assumptions used:

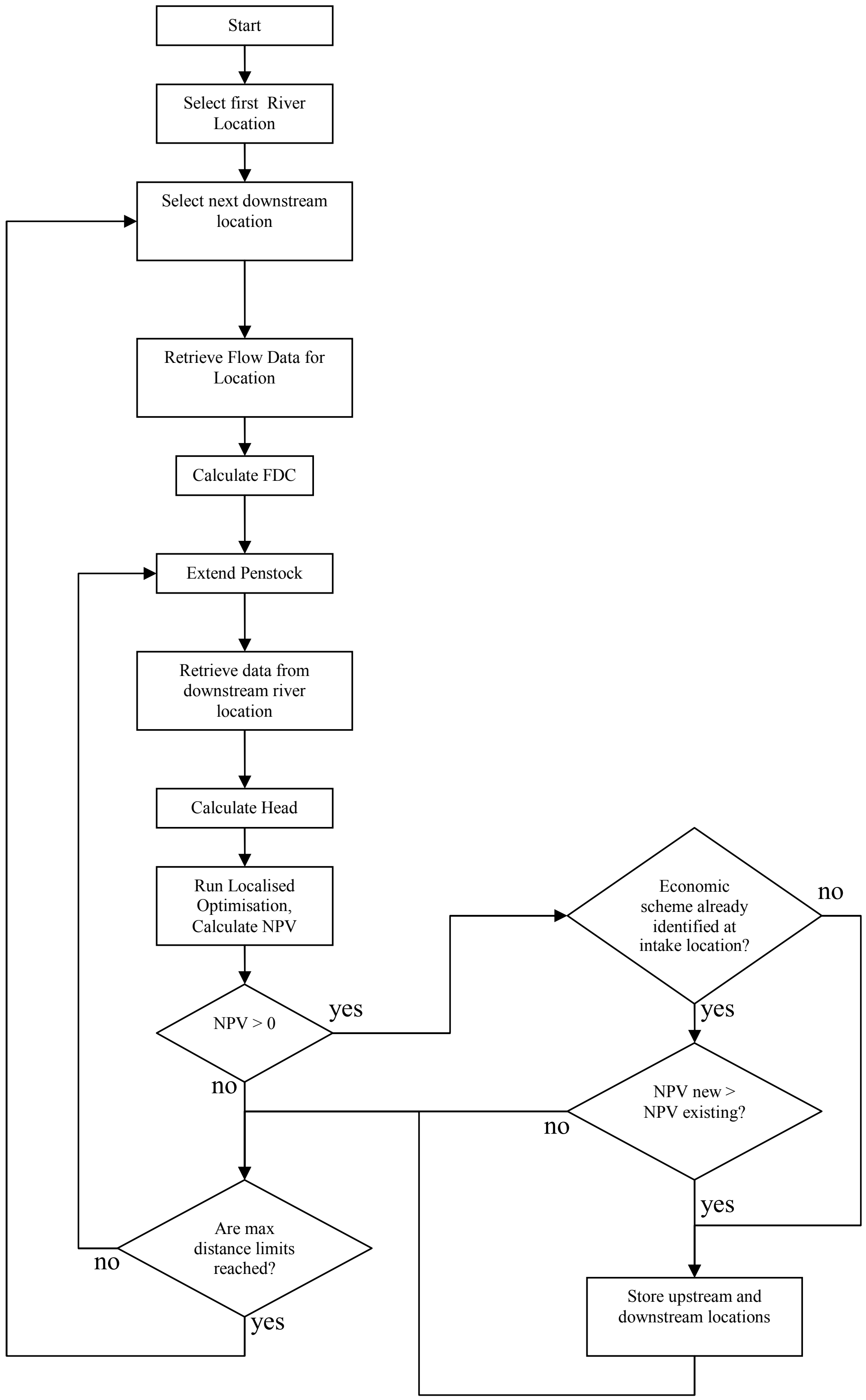


Figure 6.2: Overview of hydro search method

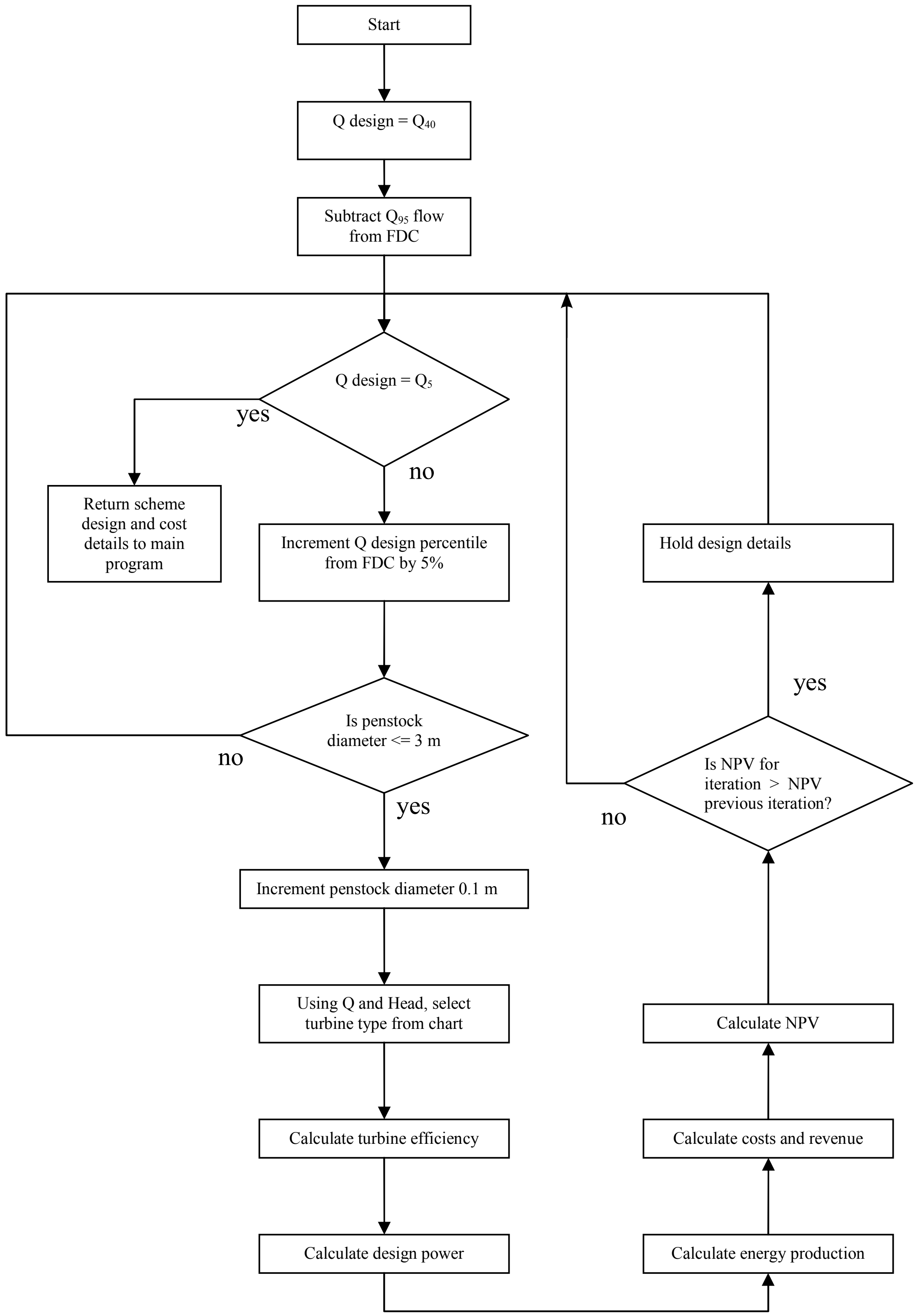


Figure 6.3: Overview of local site optimisation

- Residual flow is assumed to be Q_{95}
- A very simple site layout has been considered utilising intake weir, single penstock and powerhouse, aqueducts and tunnels are not considered.
- Only single turbine configurations have been considered.
- A new transmission line is created for each site to existing infrastructure
- A new access road is created for each site
- Electrical losses have been set at 2 % for the transmission line and 2 % for the generators
- Connections are made at 33 kV only
- A single penstock material glass reinforced plastic (GRP) is considered.
- Only three turbine types are considered Kaplan, Francis and Pelton
- Electricity prices have been assumed to be fixed as per a long term power purchase agreement.
- Construction is assumed to take place in and be completed by the end of year 0

Only projects utilising single turbines have been considered. For larger schemes a developer is likely to consider multiple turbines to allow maintenance or increase the overall turbine efficiency across the flow range. The design flow is considered to be the maximum flow the scheme is capable of using rather than the design flow of the turbine.

6.3.2 Overview

Figure 6.4 provides an illustration of how the search method operates. The search starts at the top of the reach placing a potential intake location, a penstock is then extended iteratively downstream to potential powerhouse locations. The purple cells show the available output from the 200 m G2G model and intake locations are only considered if modelled flow data is available at that point. A sanity check is performed comparing the catchment area assigned to the river location with the G2G model catchment area, if the discrepancy is below 20% then the flow data is deemed suitable for the location.

Figure 6.4(a) shows the powerhouse/penstock locations trialled for a given intake. These are compared based upon the NPV of the potential locations with the scheme with the greatest NPV (the yellow dot in this case) retained and the other schemes dismissed. The search moves downstream and the process is repeated. Figure 6.4(b) shows the potential combinations trialled further downstream; again the site with highest NPV (yellow dot) is kept. Figure 6.4(c) shows the two schemes that have been identified. As they conflict each other a method is required to choose between the potential sites. To identify conflicting schemes a search is started at the top of the river reach moving downstream. When a stored intake is identified the search moves downstream until the related powerhouse is found. If an other intake is found during this process then a conflicting site is assumed and a comparison between the two sites is performed with the site with highest NPV retained and the the lower NPV site dismissed as shown in Figure 6.4(d).

To constrain the search, the penstock extension from an intake is stopped if a required head value is not reached within a specified length, i.e., a minimum slope must be achieved within a certain length of extension. These are: 20 m after 1000 m and 250 m after 5000 m. The total length of penstock is limited to 10 km and the search is considered complete if either this 10 km limit or the sea is reached.

6.3.3 Penstock Routing

The penstock is extended downstream following the route of the river in 50 m increments, to determine the length of penstock used in the scheme the river length in the x and y dimensions is considered together with change in elevation z dimension to get a more accurate portrayal of the penstock length. If the only the x and y planes were considered then the penstock length would be underestimated in regions of steep slope. The length of penstock L_p is therefore calculated based upon the 3 dimensional euclidean distance between river points using:

$$L_p = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2} \tag{6.1}$$

where x_1,y_1 and x_2,y_2 are the OS Easting and Northing for the river point and z_1,z_2 are their elevations . The calculated length for each movement downstream is kept as a running total, giving L_p at each hydro site trial.

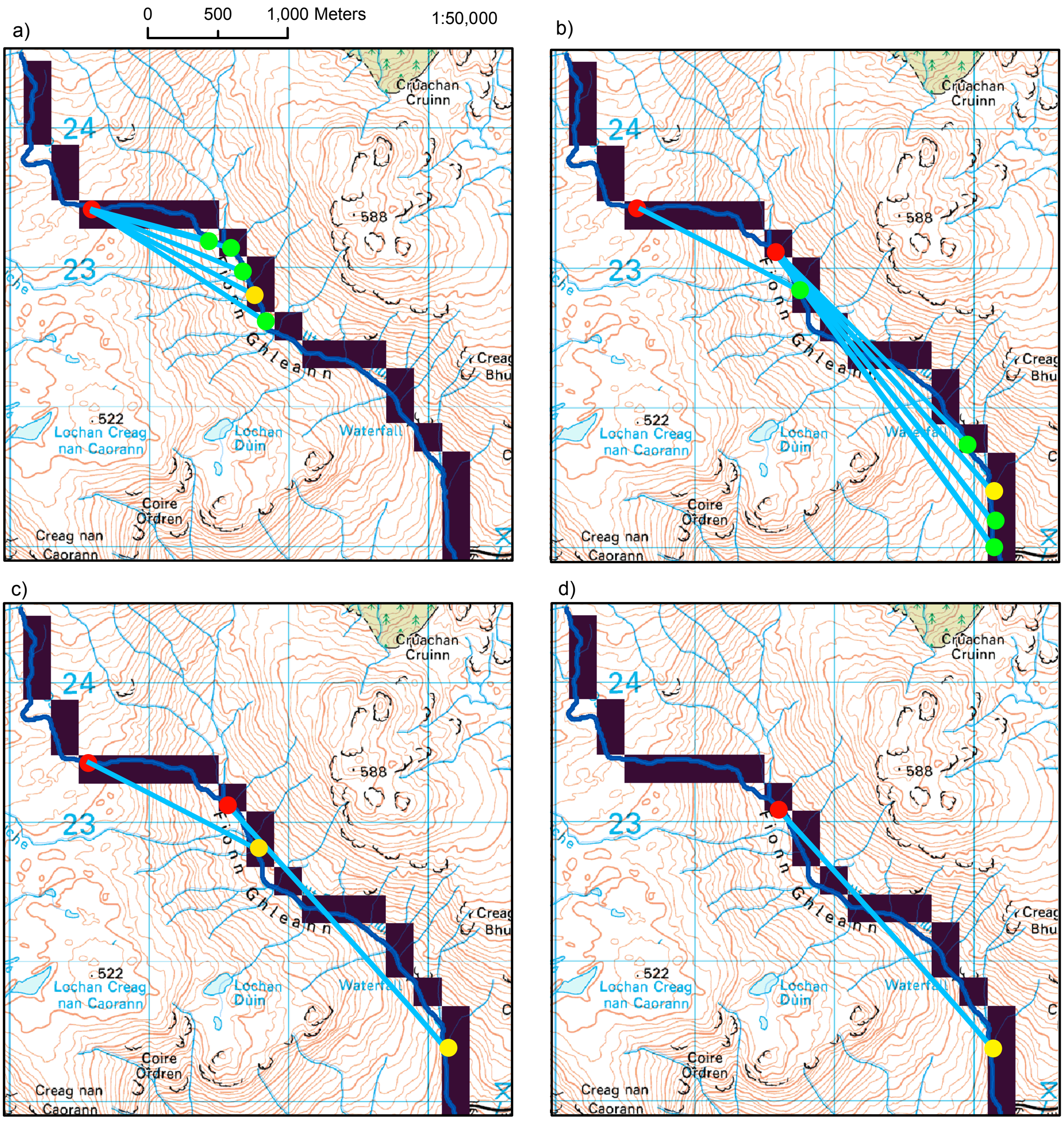


Figure 6.4: Example of hydro search operation

6.3.4 Site Layout

A real hydro scheme may incorporate a canal following a contour, or possibly a tunnel to maximise the available head while minimising penstock length and overall construction costs. This study has only considered a simple layout where the penstock is laid beside the river section between the intake and powerhouse. It is anticipated that further design work would be carried out on identified sites to determine if a more appropriate penstock route or canal/tunnel configuration can be achieved.

6.3.5 Design Flow and Penstock Diameter

The flow duration curve (FDC) is calculated from the flow data contained in the database for the intake cell. Points at 5% intervals are extracted from the FDC to allow the FDC to be represented by 21 values, Q_0,Q_5,...,Q_{100} (see Figure 6.5) (RETscreen International, 2004). This is referred to as the model FDC or Q_n with subscript n used here to refer to the 21 model FDC percentiles. The required residual flow is assumed to be the Q_{95} flow, subtracted from the model FDC, to give the flow available to the scheme Q'_n:

$$Q'_n = max(Q_n - Q_{95}, 0) \tag{6.2}$$

A range of potential design flows Q_d can then be iteratively selected from Q'_n forming the outer loop of the optimisation procedure. The flow utilised by the scheme is calculated using:

$$Q''_n = min(Q_d, Q'_n) \tag{6.3}$$

The diameter of the penstock for a given design flow determines the level of head losses caused by friction. However, the cost of the penstock is related to its diameter making the choice of penstock diameter an important variable for the project economics. The choice of optimal penstock diameter has been achieved by trialling different penstock diameters for a given design flow to determine the optimal diameter. An initial estimate of penstock diameter d_p (m) is calculated using the Manning formula for a fully closed circular cross section pipe :

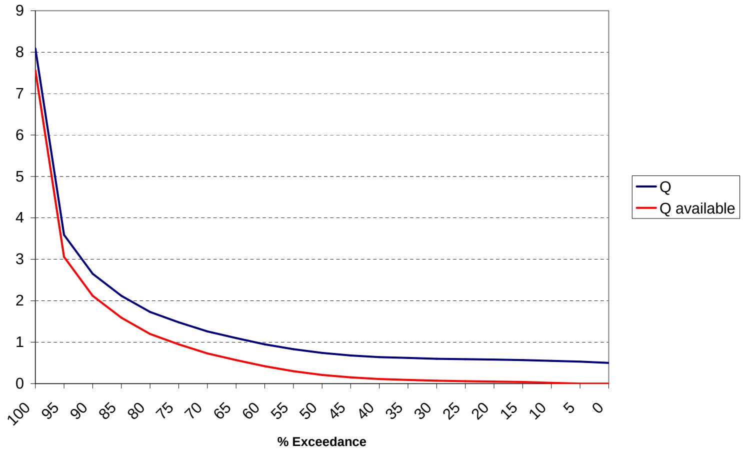


Figure 6.5: Flow duration curve with residual flow Q_{95} subtracted to give available flow

$$\frac{hf}{L_p} = \frac{10.3n^2Q_d^2}{d_p^{5.33}} \tag{6.4}$$

where hf is the headloss due to friction (m), L_p in is the length of penstock (m), n is Manning number for GRP pipe (0.009); and Q_d is design flow (m^3s^{-1}). Given a maximum allowance of 4% headloss the above can be rearranged with gross head H incorporated to give:

$$d_p = 2.83\left(\frac{L_p^2Q^2}{H}\right)^{0.1876} \tag{6.5}$$

This simple estimate is useful as a starting point for sizing the penstock, and is used to set upper and lower limits of ±20% of the calculated diameter to limit iterations of the detailed sizing method. Penstock diameter is increased by 0.1 m increments within the ±20% range. Head losses due to friction at the design flow and lower flows are then calculated using the Darcy friction factor f (Penche, 2004).

The average water velocity V within the penstock is calculated at the design flow Q_d for a given penstock diameter d_p:

$$V = \frac{4Q_d}{\pi d_p} \tag{6.6}$$

The Reynolds number R_e is then calculated:

$$R_e = \frac{d_p V}{v} \tag{6.7}$$

where v is the kinematic viscosity of water (1.31×10^{-6} m^{2}s^{-1}). From the Reynolds number the Darcy friction factor f is calculated by numerically solving the Colebrook White equation:

$$\frac{1}{\sqrt{f}} = -2log_{10}\left(\frac{\epsilon/d_p}{3.7} + \frac{2.51}{Re\sqrt{f}}\right) \tag{6.8}$$

where ϵ is roughness height (0.029 mm for GRP).

The calculated friction factor is essentially worst case at maximum flow. The headloss due to friction hf across the utilised flow range Q_n'' is calculated based upon this worst case friction factor. Equation 6.6 is used to calculate the velocity range V_n from Q_n'', allowing headloss across the flow range hf_n to be calculated using the Darcy-Weisbach equation:

$$hf_n = f\left(\frac{L}{d_p}\frac{V_n^2}{2g}\right) \tag{6.9}$$

The specified net head of the site h is calculated by subtracting the worst case friction headloss hf at maximum flow Q_d from gross head H:

$$h = H - hf \tag{6.10}$$

Values of net head h_n across the utilised flow range Q_n'' are similarly calculated:

$$h_n = H - hf_n \tag{6.11}$$

The pressure rating of the penstock must be chosen based upon the calculated surge head that may be experienced by the penstock. An appropriate pressure rating is calculated using celerity values published in Flowtite data-sheets for a range of pipe diameters and pressure ratings. Surge head h_s is calculated by multiplying the penstock pressure wave celerity rating a in ms^{-1} and the maximum flow velocity V

$$h_s = \frac{aV}{g} \tag{6.12}$$

where g is gravitational constant (9.81 ms^{-2}).

The total head h_t applied to the penstock is calculated by adding the gross head H to the surge head h_s:

$$h_t = h_s + H \tag{6.13}$$

Finally h_t is transformed from a head in m to a pressure P_s in bar to allow comparison with available penstock ratings using:

$$P_s = gh_t \tag{6.14}$$

The calculated penstock diameter and pressure rating are then compared to a lookup table of available penstocks and the option that meets the minimum requirements is selected.

6.3.6 Turbine Selection

Numerous turbine designs are available, each tailored for different site head and flow conditions. Three turbine designs have been chosen, Pelton, Francis and Kaplan respectively providing options for high, medium and low head sites.

Turbine selection rules were developed using a typical turbine range chart (Figure 6.6), where site gross head H in m and design flow Q_d in m^3s^{-1} form the criteria for selection. Pelton turbines are selected for low flow-high head sites using the following rule:

> IF ($Q_d \leq 2$ AND $H > 100$) OR ($Q_d \leq 0.5$ AND $50 < H \leq 100$) THEN $turbine = Pelton$

For high head sites up to 300 m with design flow greater than 2 m^3s^{-1} and medium head sites a Francis turbine is selected :

> IF ($2 < Q_d \leq 20$ AND $100 < H \leq 300$) OR ($0.5 < Q_d \leq 20$ AND $20 < H \leq 100$) THEN $turbine = Francis$

For low head sites a Kaplan turbine is selected with design flow up to 50 m^3s^{-1}:

> IF ($20 < Q_d \leq 50$ AND $H \leq 50$) OR ($0.5 < Q_d \leq 20$ AND $H \leq 20$) OR ($Q_d \leq 0.5$ AND $H \leq 50$) THEN $turbine = Kaplan$

The range covered by the three turbine types was assumed to cover the majority of site conditions. In instances where no suitable turbine type is available it is expected that the site optimisation function will lower the design flow until a suitable turbine type is found.

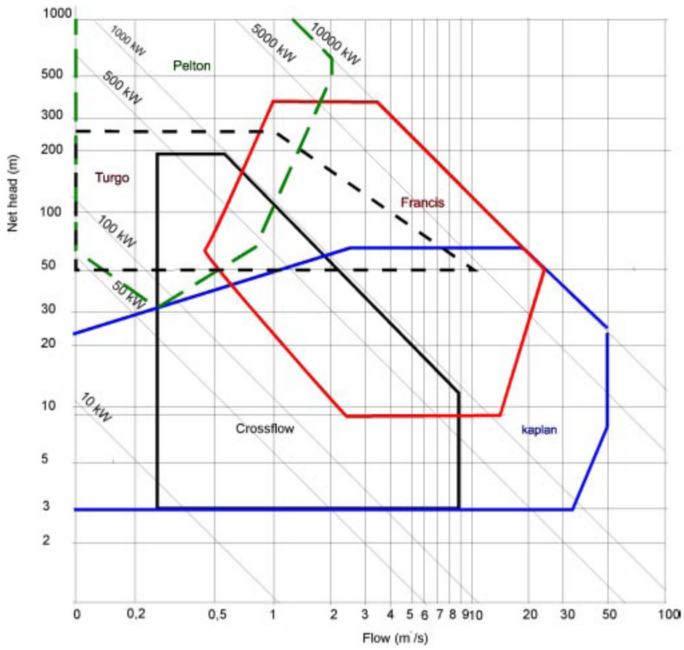


Figure 6.6: Turbine Selection Chart, (Penche, 2004)

In this study only single turbine installations have been considered. Combinations of 2 or more turbines allow a turbine efficiency curve to be tailored for the whole flow regime, increasing overall efficiency and yield. In addition, multiple turbines may offer cost savings when flow rates are very high and allow partial operation to be continued during maintenance periods. Ideally, the search function would consider a multiple turbine scenario, however, this would add significant complexity and run time.

6.3.7 Turbine Sizing and Efficiency

The RETScreen software provides a method for calculating energy production from water turbines using empirically derived equations to allow turbines to be sized based upon head and flow (RETscreen International, 2004). Based upon the turbine size and type an efficiency curve across the turbine operational range can be computed. The RETscreen methodologies are well established and validated and it is therefore sensible to take a similar approach here.

6.3.7.1 Reaction Turbines

Reaction turbines are sized by determining the runner size and specific speed, the method for determining Francis and Kaplan turbine size and efficiency will be detailed here. Runner diameter d is calculated from design flow Q_d:

$$d = kQ_d^{0.473} \tag{6.15}$$

where k is an empirical constant given the value of 0.46 for $Q_d < 1.8$ m^{3}s^{-1} or 0.41 for $Q_d \geq 1.8$ m^{3}s^{-1}. Specific speed (n_q) is then calculated based upon net head h:

$$n_q = k_q h^{-0.5} \tag{6.16}$$

where k_q is a constant determined by turbine type and given the value 800 for Kaplan turbines and 600 for Francis turbines. Once the turbine size is determined the efficiency curve can be calculated. An adjustment to the turbine peak efficiency $\hat{e}_{nq}$ is made based upon the calculated specific speed n_q:

$$\hat{e}_{nq} = \left\{(n_q - 56)/256\right\}^2 \tag{6.17}$$

A similar adjustment to peak efficiency $\hat{e}_d$ based upon runner size d is made:

$$\hat{e}_d = (0.081 + \hat{e}_{nq})(1 - 0.789d^{-0.2}) \tag{6.18}$$

Turbine peak efficiency e_p is then calculated:

$$e_p = (0.919 - \hat{e}_{nq} + \hat{e}_d) - 0.0305 + 0.005R_m \tag{6.19}$$

where R_m is a turbine design coefficient that can be altered to reflect the characteristics of different manufacturers machines. Here it has been left to the default value of 4.5.

The peak efficiency flow (Q_p) will have a lower value than the design flow Q_d, as design flow is considered to be the scheme maximum flow rate. Peak efficiency will typically occur at approximately 70% of the peak flow. Q_p is calculated based upon Q_d and specific speed n_q:

$$Q_p = 0.65Q_d n_q^{0.05} \tag{6.20}$$

Efficiencies at flows above and below the peak efficiency flow Q_p are then calculated to enable an efficiency curve to be produced. Efficiencies below peak e_n are calculated based upon the ratio of flow through the turbine Q_n'' (for flows $Q_n'' < Q_p$) to the peak efficiency flow Q_p multiplied by the peak efficiency e_p with adjustment made for the specific speed n_q, using:

$$e_n = \left\{1 - \left[1.25\left(\frac{(Q_p - Q_n'')}{Q_p}\right)^{(3.94-0.0195n_q)}\right]\right\} e_p \tag{6.21}$$

Efficiencies at flows above peak efficiency flow are determined by first calculating the drop in efficiency that occurs when the turbine is operating at full load based upon specific speed n_q:

$$\hat{e}_p = 0.0072n_q^{0.4} \tag{6.22}$$

The efficiency at full load e_r is then calculated by modifying the peak efficiency e_p with this adjustment $\hat{e}_p$:

$$e_r = (1 - \hat{e}_p)e_p \tag{6.23}$$

Efficiencies at flows above peak efficiency flow (e_q) are then calculated for flows $Q_n'' \geq Q_p$:

$$e_n = e_p - \left[\left(\frac{Q''_n - Q_p}{Q_d - Q_p} \right)^2 (e_p - e_r) \right] \tag{6.24}$$

6.3.7.2 Impulse Turbines

The only impulse turbine type considered was the Pelton turbine and it is treated differently to the reaction turbine. A key configuration property of Pelton turbines is the number of jets that the machine possesses which can have a large bearing upon the machine efficiency. For simplicity all Pelton turbines have been considered to have only a single jet.

The rotational speed (n) is calculated based upon net head h, design flow Q_d and the number of Pelton jets j:

$$n = 31 \left(h \frac{Q_d}{j} \right)^{0.5} \tag{6.25}$$

Runner diameter d is calculated from rotational speed n:

$$d = \frac{49.4 h^{0.5} j^{0.02}}{n} \tag{6.26}$$

Turbine peak efficiency e_p is calculated from runner diameter:

$$e_p = 0.864 d^{0.04} \tag{6.27}$$

Peak efficiency flow (Q_p), occurs below the design flow Q_d and is calculated from:

$$Q_p = (0.662 + 0.001 j) Q_d \tag{6.28}$$

Finally, the full turbine efficiency curve can be created by determining efficiency at flows above and below peak efficiency flow e_n using:

$$e_q = \left[1 - \left\{ (1.31 + 0.025 j) \left| \left(\frac{Q_p - Q''_n}{Q_p} \right) \right|^{(5.6 + 0.4 j)} \right\} \right] e_p \tag{6.29}$$

6.3.7.3 Accuracy of turbine efficiency curves

Model efficiency curves have been developed for the three turbine types: Francis, Pelton and Kaplan; these are shown in Figure 6.7. The curves appear realistic with efficiency peaking below maximum flow and dropping off below 40 % of rated flow. Example curves for real machines (BHA, 2005) are shown in Figure 6.8 illustrating the expected performance of different turbine types. These are similar to the computed curves although the peak efficiency of the computed Francis curve is about 5% higher.

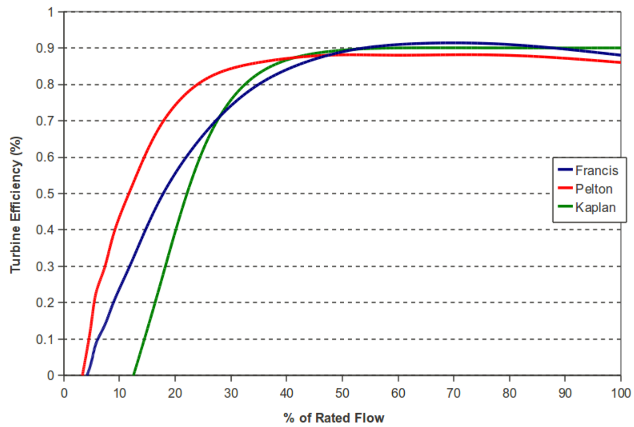


Figure 6.7: Efficiency curves for Kaplan (gross head=25 m, Rated flow = 12.02 m^3s^{-1}); Francis and Pelton (gross head = 214 m, Rated flow = 1.2 m^3s^{-1})

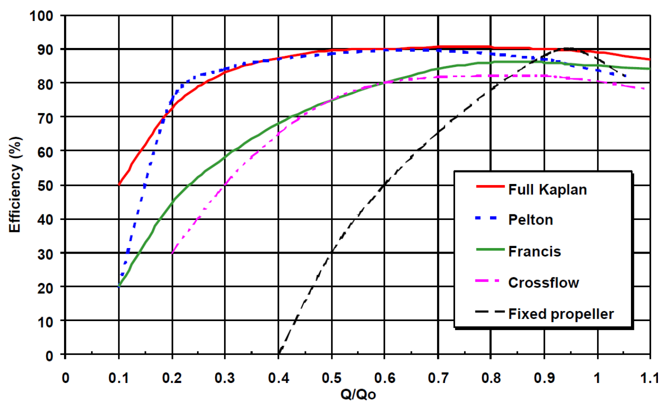


Figure 6.8: Example Turbine Efficiency Charts (BHA, 2005)

Without access to manufacturers' data it is difficult to perform further validation of the model efficiency curves. However, they are considered realistic enough to be adequate for use in a resource assessment.

6.3.8 Power Production and Energy Yield

Calculation of power production and annual energy yield is developed from the RETscreen method (RETscreen International, 2004) with design power P_{des} calculated based for the design flow Q_d at net head using the hydropower equation:

$$P_{des} = \rho g Q_d h e_{des} e_g (1 - l_{trans})(1 - l_{para}) \tag{6.30}$$

Here ρ is the density of water (1000 kg/m^3); e_{des} is the turbine efficiency at the design flow Q_d, e_g is generator efficiency (taken to be 0.98); and l_{trans} and l_{para} are the percentage losses expected from the transformer and transmission line, respectively (both taken to be 2%).

Power as a function of flow P_n is similarly calculated, using headloss across the flow range h_n as calculated in section 6.3.5:

$$P_n = \rho g Q''_n h_n e_n e_g (1 - l_{trans})(1 - l_{para}) \tag{6.31}$$

This allows a power production curve showing generation levels over the range of flows Q''_n to be created. From this an average annual energy yield can be calculated and used to determine average annual revenue from electricity sales. As the the power production curve P_n is composed of 5% increments each value can be considered to be the power produced for 5% of the 8760 hours in a year. l_{dt} represents the downtime experienced during a year (%), set to 2%.

$$E_{avail} = \sum_{20}^{n=1} \left(\frac{P_{n-1} + P_n}{2} \right) \frac{5}{100} 8760(1 - l_{dt}) \tag{6.32}$$

Power time series are calculated using the power curve developed from equation 6.31. The 5 % value of flow corresponding to the daily mean flow value is determined allowing the corresponding power from the power curve to be taken as the production in MW associated with that flow. When the daily average flow lies between two 5% increments the power is linearly interpolated from the two closest values of P_n.

6.4 Costing Methodology

A detailed costing approach is incorporated in the RETScreen software developed for North American Hydro projects based upon the methods of Gordon (Gordon, 1981; Gordon and Noel, 1986; Gordon and Penman, 1979; Gordon, 1983; RETscreen International, 2004). Ideally empirical cost functions would be developed using recent UK small medium hydro projects but as this information is not readily available the RETScreen approach has been employed to generate a large proportion of the costs. Recent data has been obtained for the cost of GRP pipelines and HV transmission lines and these have been incorporated to create a hybrid costing method.

6.4.1 Assumptions and Limitations

The RETScreen costing method has been developed from a costs dataset of North American hydro plant. It is unclear how old these schemes are or exactly when the analysis was undertaken. It is therefore assumed that the developed costs, once converted to £(2011), will be representative of the costs that would be expected for a hydroplant developed in Scotland.

The RETScreen formulas provide costs in 2003 Canadian Dollars. To convert to £(2011) two corrections were applied. Firstly a 2003 Canadian Dollar / Sterling conversion rate C_{ex} of 0.45 was applied based upon the average exchange rate for that year giving a value in £(2003). A conversion factor C_{inf} to inflate these values to £(2011) was applied using

$$C_{inf} = (1 + i_{inf})^n \tag{6.33}$$

where i_{inf} is the rate of inflation, chosen to be 2.5 % and n is the number of years to be inflated over (here 8 years). C_{inf} and C_{ex} are then multiplied to give a combined conversion factor C_{con}:

$$C_{con} = C_{inf} \times C_{ex} \tag{6.34}$$

The conversion C_{ex} is applied to item costs developed in Canadian Dollars using the RETScreen formulas. Certain costs such as installation costs are calculated as a function of the item cost and as the item cost has already been converted to £the conversion is not applied to these secondary costs.

The conversion can be calculated the other way round by inflating Canadian dollars then converting to Sterling. However, due to marked appreciation of the Canadian Dollar against Sterling in recent years, the result is significantly different, leading to much higher Sterling cost estimations. This highlights the uncertainty introduced by inflation and currency fluctuations.

6.4.2 Turbine, Generator and Control

The electromechanical equipment required for a project includes a water turbine, turbine governor and generator. RETScreen lumps the turbine and governor together but treats the generator separately. Generator costs are common for all turbine types and are calculated based upon the design power P_{des} in MW of the site and the gross head H using the following:

$$C_1 = 0.82n^{0.96}\left(\frac{P_d}{H_g^{0.28}}\right)^{0.9} \times 10^6 \times C_{con} \tag{6.35}$$

where n is the number of turbines, in this case 1. Costs for Kaplan, Pelton and Francis turbines are calculated using specific equations. The cost of reaction turbines is determined by the size of runner diameter d and gross head H of the site.

The cost of a Kaplan turbine and governor is given by:

$$C_2 = 0.27n^{0.96}d^{1.47}(1.17H^{0.12} + 2) \times 10^6 \times C_{con} \tag{6.36}$$

and for a Francis turbine and governor by:

$$C_2 = 0.17n^{0.96}d^{1.47}((13 + 0.01H_g)^{0.3} + 3) \times 10^6 \times C_{con} \tag{6.37}$$

Pelton turbine and governor costs are calculated based upon the site gross head H and the design power P_{des} in MW. RETScreen provides two variations of the following formula for large and small Pelton turbines, it was found that the formula for small turbines generated significantly greater costs making Pelton turbines considerably more expensive than other types. Only the equation for larger Pelton turbines has been used here and an additional reduction factor of 0.5 has been applied to Pelton turbine costs to bring them to the same level as other turbines.

$$C_2 = 3.47n^{0.96}\left(\frac{P_d}{H_g^{0.5}}\right)^{0.44} \times 10^6 \times 0.5 \times C_{con} \tag{6.38}$$

Installation costs for the turbine, governor and generator are calculated as a fraction of the total cost of these items using:

$$C_3 = 0.15(C_1 + C_2) \tag{6.39}$$

6.4.3 Penstock

Traditionally small hydro site penstocks have been constructed from steel. In recent years GRP pipe has become more cost effective and newer sites will generally use this material. RETScreen penstock costing is assumed to be based upon steel penstocks, producing extremely high values with typical penstock costs exceeding 1000 £/m. To provide a more accurate representation, Penstock costs C_4 are generated based upon quoted cost data. Cost data was provided by Johnston Pipes (2010) for a small range of penstock diameters and pressure rating; these have been extrapolated to cover a fuller range of pressure ratings and diameters (see Figure 6.9) based upon those available from industry leader Flowtite (Amiantit Group, 2010). A lookup table was created containing available pipe diameters, pressure ratings, weights, celerity values and unit costs based upon the extrapolated figures.

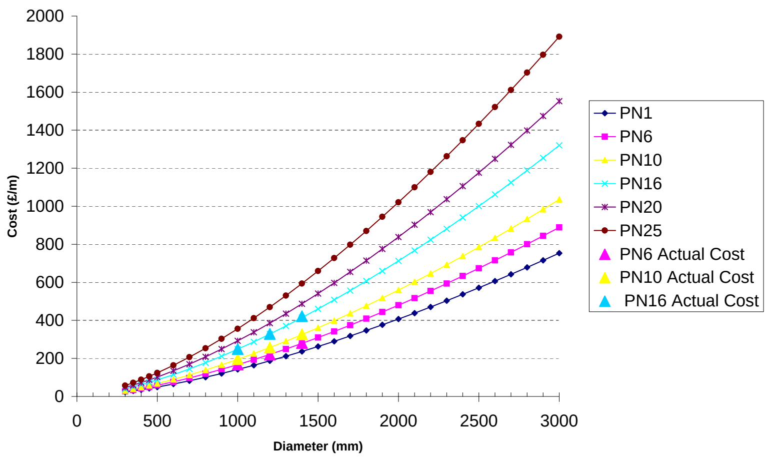


Figure 6.9: Estimated costs of penstocks with diameter 0.3 m to 3 m for different pressure ratings (PN)

RETscreen calculates installation costs as a function of the penstock weight. This method has been retained with weight of the GRP penstock entered as W in the following equation:

$$C_5 = 5W^{0.88} \times C_{con} \tag{6.40}$$

6.4.4 Civil Structures

Civil structures include the weir, intake works, powerhouse and tailrace. The cost of these are calculated based upon the design power of the scheme P_{des}, the gross head of the site H, the distance to borrow pits l_b (assumed to be 0.5 km), and the length of crest of the dam or weir l_d which is given a fixed value of 10 m.

$$C_6 = 1.97n^{-0.04}\left(\frac{P_d}{H^{0.3}}\right)(1 + 0.01l_b)\left(1 + 0.005\frac{l_d}{H_g}\right) \times 10^6 \times C_{con} \tag{6.41}$$

6.4.5 Substation and Transformer

A substation and transformer are required to step up the voltage at the generator terminals from typically around 1000 V to the transmission voltage. The cost of the transformer and substation are determined by the number of generators n (here always 1), design power P_d in MW and the transmission voltage in this case 33 kV using:

$$C_7 = (0.0025n^{0.95} + 0.002(n + 1)\left(\frac{P_d}{0.95}\right)^{0.9} V^{0.3} \times 10^6 \times C_{con} \tag{6.42}$$

The installation costs of the transformer and substation are calculated as a fraction of cost C_6 using:

$$C_8 = 0.15C_7 \tag{6.43}$$

6.4.6 Transmission Lines

A single connection voltage of 33 kV has been used as this is capable of transfer of up to 25 MW over distances up to of 30 km with acceptable levels of losses ($\leq$ 3%). It is assumed that connections will be made to primary substations with a 33 kV busbar or to existing 33 kV lines. While it is possible that small hydro sites with capacity below 2 MW may be connected at 11 kV, the distance this voltage can transfer power before losses and voltage rise become unacceptable is much lower (around 5 km for a 2 MW installation). In addition, the locations of 11 kV lines are not readily available due to the complexity of the network at this voltage level. Connections to lines at voltages in excess of 33 kV typically require a new substation costing in excess of £1,000,000. For these reasons only connection at 33 kV is considered.

Costs for 33 kV overhead line is based on published utility cost data suggest a range of costs from £1,550 to £8,715 for a 70 m span line giving a range of 22£/m to 124.5£/m (SHEPD, 2011). The mid point of this range gives a cost of 73.25£/m which has been taken as the unit cost of transmission line. When connecting to an existing 33 kV line, it is assumed that a simple tee connection can be made. This is priced at £50,000 based on the cost of two additional sets of utility switchgear, one at the tee and a second at the hydro scheme step up transformer. When connecting at a primary substation it is assumed that an additional connection can be made to an existing 33 kV busbar at a cost of £150,000 based upon the example 7A provided in SHEPD (2011). In both cases, an additional factor of 1.25 is applied to lone costs to represent non-ideal line routing. This gives the following cost functions for line connections:

$$C_9 = L_{d,line} \times 73.25 \times 1.25 + 50,000 \tag{6.44}$$

where $L_{d,line}$ is the distance in m to the nearest 33 kV transmission line. For substation connections:

$$C_9 = L_{d,sub} \times 73.25 \times 1.25 + 150,000 \tag{6.45}$$

where $L_{d,sub}$ is the distance to the nearest primary substation.

The length of transmission line for connection has been determined using a least cost route method that is designed to avoid water bodies. Similarly to Boehme (2006) and Garrad Hassan (2001), a cost grid has been developed at 200 m resolution with land squares given a value of 1 and water squares given a value of 10. Vector maps of line and substation location were developed from SHEPD and Scottish Power Distribution's Long Term Development Statements (SHEPD, 2010; SP Distribution, 2010). The cost grids together with vector files detailing the 33 kV network and the locations of primary substations allow distance grids to be created which give the least cost route distance to the nearest 33 kV lines or primary substations from a river point. Both substation and line connections are costed at each point with the connection type with lowest cost selected.

6.4.7 Access Costs

Access road costs have been calculated using the following RETScreen equation:

$$C_{10} = 0.025TA^2 l_a^{0.9} \times 10^6 \times C_{con} \tag{6.46}$$

where T is a cost reduction factor that is set to 0.25 for unpaved roads (referred to as tote roads in the RETScreen documentation) with all roads assumed unpaved in this case. A is an access difficulty set between 1 and 6 based upon the difficulty of terrain which is set here to 2.

A least cost routing method was used to determine the cost of access roads similar to the method used in the previous section. A vector file of the Scottish road network including unclassified roads such as forestry roads was used with a cost surface where cells with slope above 20% and areas of water were set to a value of 10 and all others were given a value of 1 (OS Meridian 2, 2009). This enabled production of a raster of least cost distances to suitable roads which were assigned to river points.

6.4.8 Other Costs

RETScreen includes costing methods for several other categories which have been utilised. Engineering design costs are calculated based upon the capacity and head of the project:

$$C_{11} = 0.37n^{0.1}E\left(\frac{P_d}{H_g^{0.3}}\right) \times 10^6 \tag{6.47}$$

A category is included called development costs, which is assumed to be the costs associated with obtaining necessary permits to allow work. This is also calculated based upon costs from the other categories:

$$C_{12} = 0.04 \sum (C_1) to (C_{11}) \tag{6.48}$$

The cost of a feasibility study is calculated based upon the other identified costs using:

$$C_{13} = 0.032 \sum(C_1)to(C_{12}) \tag{6.49}$$

Finally a cost entitled 'Miscellaneous' is included as a function of the other costs and the design flow of the project:

$$C_{14} = 0.25iQ_d^{0.35} \times 1.1 \sum(C_1)to(C_{12}) + 0.1 \sum(C_1)toC_{10}) \tag{6.50}$$

where i is the interest rate of finance (assumed in this case to be 10%). It was initially debated whether to include this cost as it can add around 20% to total project costs and its meaning is not clearly defined. Ultimately it has been included as it is assumed to represent a project management risk mitigation strategy. Identifying the value for risk (in this case based upon design flow and cost of finance) by multiplying budgeted costs by these values in case of project overspend due technical complications or other mishaps.

6.5 Project Economics

6.5.1 Optimisation Function

As discussed in section 6.3, the hydro search performs local site optimisation to determine the optimum choice of design flow and penstock diameter.

Choice of design flow Q_d is a trade off between increased energy production and capital costs. As design flow is increased the size of turbine and penstock are increased allowing a greater proportion of the site flow regime to be put to use increasing energy production and revenue. Increasing plant size will decrease the capacity factor as the there will be less time spent operating at the peak capability of the site; maintenance costs will also rise reducing revenues.

An initial diameter estimate is calculated using Equation 6.5 and penstock sizes around this estimate are then trialled. Figure 6.10 shows the change in NPV as penstock diameter is increased, NPV increases dramatically as penstock diameter is increased due to reduced head-losses. The improvement levels off once a diameter of 1.1 m is reached and this is chosen as the optimal penstock diameter. The performance begins to decline with greater penstock size as the improvements in headloss are negated by increased penstock costs.

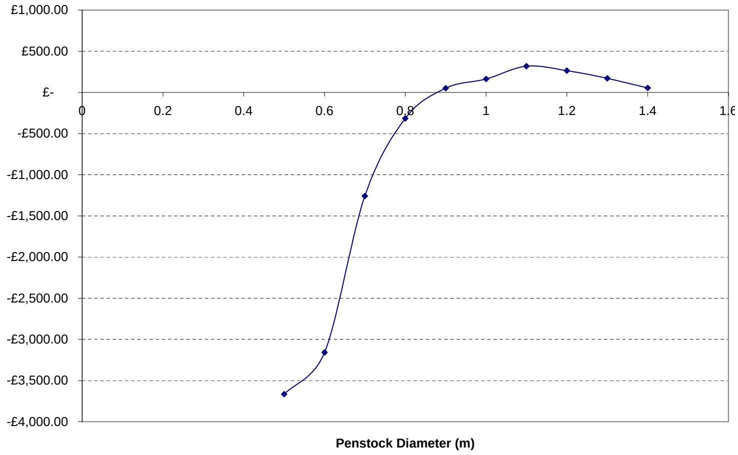


Figure 6.10: Impact of varying penstock diameter on NPV

Figure 6.11 shows the increase in energy production as design flow is increased for a typical site; the curve steepens above Q_{50} as the design flow is set at higher flow stages of the FDC. The rate of increase declines between Q_5 and Q_0, where the change in plant size is greatest, at Q_0 the turbine efficiency curve will rapidly drop off from peak efficiency as flow reduces below design flow, reducing overall efficiency of the site.

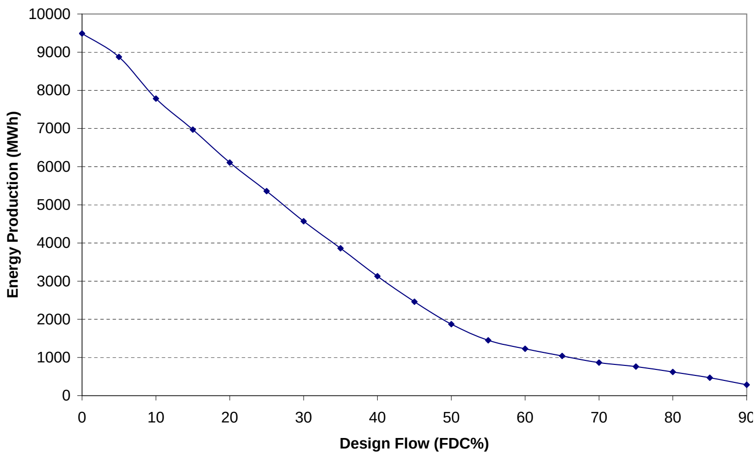


Figure 6.11: Change in energy production as design flow is increased

Figure 6.12 show the change in capacity factor as design flow increases. Between Q_{40} and Q_{50} capacity factors in the range 0.5 to over 0.6 are achieved, which corresponds with published capacity factor values expected for typical hydro plant. Capacity factor declines steadily as design flow is increased, with a more rapid decline occurring between Q_5 and Q_0, where capacity increases the most.

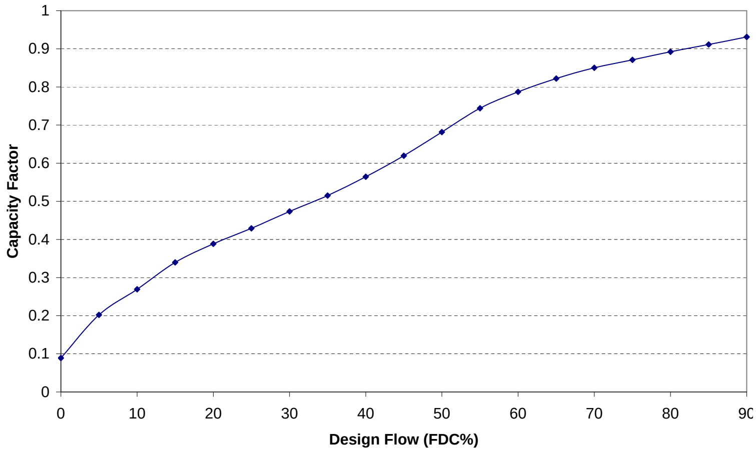


Figure 6.12: Change in capacity factor as design flow is increased

To show the impact of design flow on economic performance the total costs are compared to the total revenues for a range of design flows (see Figure 6.13). The NPV is shown by the space between the revenue and cost curves. In this case discounted revenue exceeds total costs at Q_{35}, which indicates this is the minimum size for economic performance. As the design flow is increased further NPV improves until Q_{20} when it starts to decline. Revenues increase until Q_5, then fall at Q_0 as the increased maintenance costs exceed the extra revenue from increased energy production. The most economic design flow, Q_{20} gives a capacity factor of 0.37 which is lower than would be expected for a hydro plant, but is comparable to capacity factors experienced in the wind industry.

This suggests that industry practice of setting design flow between Q_{40} and Q_{60} is somewhat conservative and site economics may be significantly improved by designing to operate with higher flows. This of course will increase the total costs, however, based upon the NPV measure can improve the overall economic performance of the site.

6.5.2 Revenue From Electricity Sales

A fixed price for electricity sales has been assumed of 45 £/MWh based upon data from the UK Wholesale Electricity Market. Half hourly market prices were obtained from a clearing house for 2008 to 2011, these were binned using intervals of £5 to create a histogram of prices for 4 years (apx power UK, 2010). The most frequently occurring prices were found to be in the range 40-45 £/MWh (see Figure 6.14), as such 45 £/MWh is assumed to be the price that generators will receive from long term electricity supply contract.

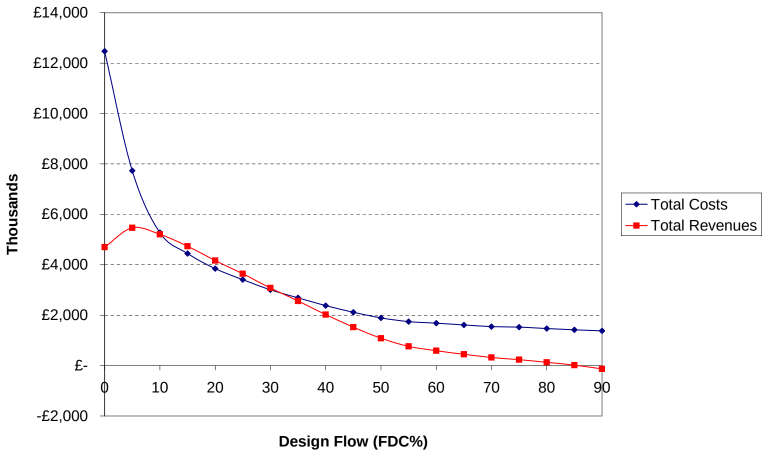


Figure 6.13: Change in costs and revenues as design flow is increased

Renewable Obligation Certificate (ROC) auction prices for 2008 to 2011 shown in Figure 6.15 were used to calculate an average price paid for ROCs (E-ROC, 2011). This was found to be £49 and is assumed to be the value received by generators for sale of ROCs. A feed in tariff (FIT) mechanism was introduced in 2010 offering 11.5p/kWh for hydro projects with installed capacity between 100 kW and 2 MW. Although this potentially offers greater income than the ROC mechanism, there is some doubt about the future of this mechanism so it has not been considered in this case.

With a change in UK Government, the ROC policy is being updated by changing the value of ROCs received by different generation types. It is proposed that the value of ROCs available for new hydroplant reduce to 0.5 ROCs, a cut in subsidy of 50%. As this decision has been challenged by several industry groups, the decision may be revoked. As such this study has used the original 1 ROC value that was previously available.

6.5.3 Comparison with other Sources of Cost Data

The IEA (2005) performed an assessment of the costs of electricity from small hydroplant. With a 5% discount rate, hydroelectricity generation costs range between 40 and 80 USD/MWh (25 to 50 £/MWh £(2005)) for all plants except one. At a 10% discount rate, hydroelectricity generation costs range between 65 and 100 USD/MWh (40 to 63 £/MWh £(2005)) for most plants. The high share of capital costs in hydropower development costs explains the large difference between costs at different discount rates.

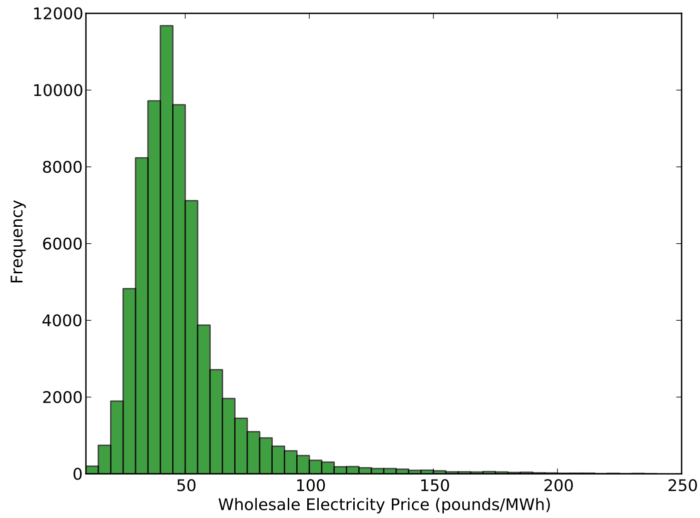


Figure 6.14: Distribution of UK wholesale electricity prices

6.5.4 Operating Costs

Maintenance costs for hydropower are considered low compared to other generation types due to the maturity of the technology and benign operating regime. Clearly unlike thermal plant there are no fuel costs that need to be accounted for. As such operation and maintenance costs were simply estimated as being 3% of total installed costs. There will be downtime associated with maintenance and this has been estimated to be 2% of the year, or approximately 7 days.

6.5.5 Cash Flow

A discounted cash flow method is used to assess project economic potential. Future net cash-flow R_t (revenue from electricity sales/ROCs less maintenance costs) are discounted on an annual basis to return them to present value (Kirschen and Strbac, 2004):

$$PV = \frac{R_t}{(1+i)^t} \tag{6.51}$$

where i is the discount rate applied and t is the number of years into the future.

A simple example has been used to assess the maximum cost of plant expenditure that can be made while still producing a positive net present value. Costs and revenues have been considered on a per kW basis, with discounted cash flows calculated for a range of installed

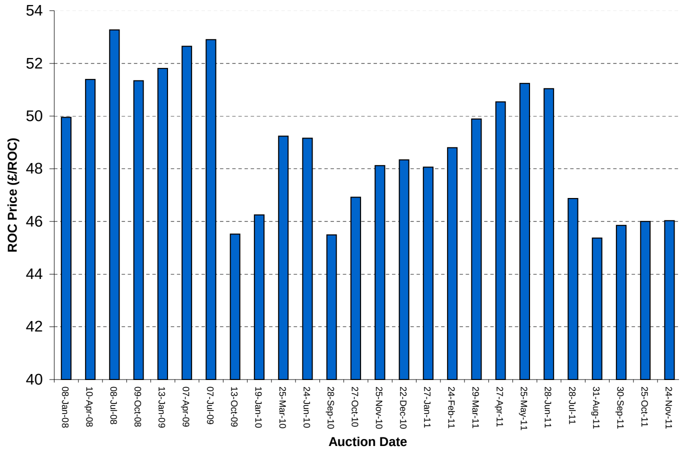


Figure 6.15: Average ROC prices achieved at auction

capacity costs assuming a 40% capacity factor, 3% maintenance costs, 100% availability and revenue of 94 £/ MW (ROC plus electricity sales as per section 6.5.2). Resulting NPV/kW at the end of a 25 year project life have been plotted against capital costs per kW for 5%, 10% and 15% discount rates in Figure 6.16. The impact of discount rate on economic plant costs (as indicated by positive NPV) is clearly seen with maximum return at 5%, 10% and 15% discount rates of £1800/kW, £2300/kW and £3250/kW, respectively.

While NPV has been used as the main measure economic performance, additional measures were calculated to aid analysis. Levelised Electricity Costs (*LEC*) are commonly used to show the inherent cost of energy by summing discounted investment expenditure I_t (all capital costs are assumed to occur in year 0) and operations and maintenance costs (assumed to be a fixed 3% of capital costs) then dividing by the sum of discounted electricity generation E_t over the n year lifetime (Kirschen and Strbac, 2004).

$$LEC = \frac{\sum_n^{t=1} \frac{I_t + M_t + F_t}{(1+i)^t}}{\sum_n^{t=1} \frac{E_t}{(1+i)^t}} \tag{6.52}$$

This provides a useful estimate of cost of electricity from sites that can be compared with other generation types in £/MWh. The discounted payback period (DPP) is calculated by counting the number of years of operation required for the NPV to become positive. This metric is useful because it is simple and intuitive. However, it should be treated with caution as inter-annual variability in rainfall could significantly extend the payback period if lower than average runoff is available during the initial years of project life.

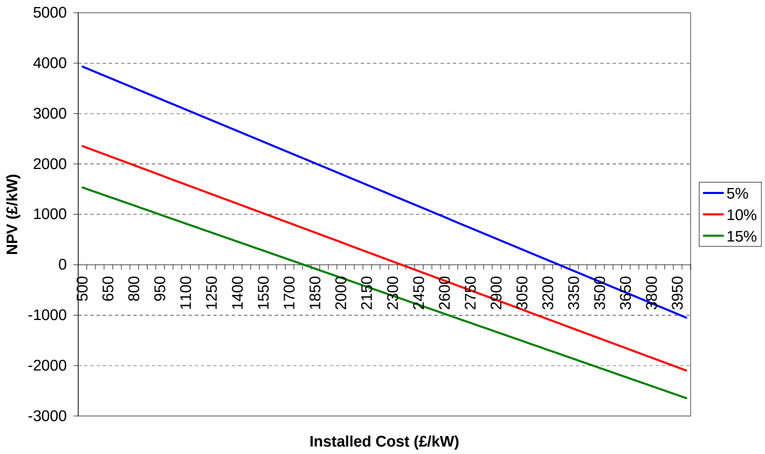


Figure 6.16: Impact of Discount Rate on Economic Capital Costs

6.5.6 Analysis of Costing Method

Using a range of potential design flows and site gross head it is possible to compute a cost surface showing how the model predicts capital costs will change with available head and flow. A fixed penstock slope of 1 in 10 has been assumed and Q_d has been restricted to Q_{25} of the FDC. Road construction and grid connection costs have been set to zero, so that the only costs are those directly associated with construction of the hydro plant.

Starting with a broad search of the space, costs were produced for a wide range of heads and flows. Figure 6.17 shows the cost surface with very high costs seen when head and flow are both low; in this case a head of 5 m and flow of 0.07 m^3s^{-1} form the minimum. As head and flow increase costs drop rapidly. Costs begin to increase again once flow exceeds 20 m^3s^{-1}. Figure 6.18 shows the corresponding NPV as a function of head and flow plotted as contour lines. The zero contour marks the boundary between economic and uneconomic schemes. High head sites are economic with very small flows, as head decreases a greater design flow is required to remain economic. A minimum head of at least 20 m is required to make a site economic.

It is expected that the majority of sites identified will have design flow rates far lower than 20 m^3s-1 , to investigate the boundary in a more credible range, the range of flows is reduced and the minimum head is increased to 15 m. This greatly impacts the minimum costs reducing lowest head sites to below 5000 £/kW for flows above 2 m^3s^{-1}, as Figures 6.19 and 6.20 show.

The critical region that will decide whether the majority of sites are feasible is below 2 m^3s^{-1} and between 20 and 150 m, so this is now explored. Figure 6.21 shows the cost curve in the

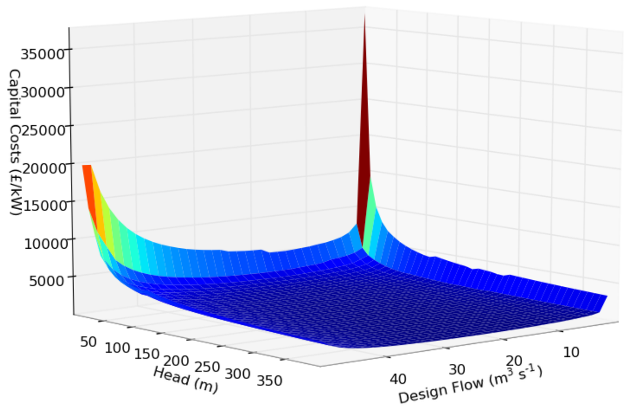


Figure 6.17: Cost surface for wide range of head and flow

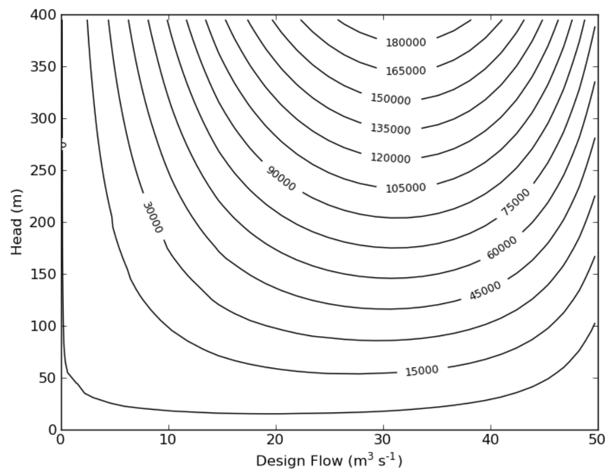


Figure 6.18: Contour plot of NPV (£thousands) against head and flow

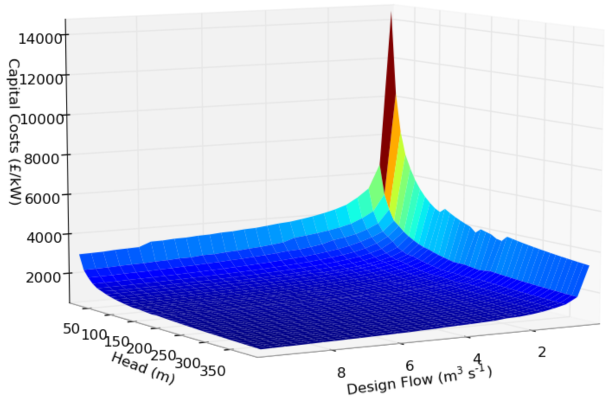


Figure 6.19: Cost surface for reduced head and flow values

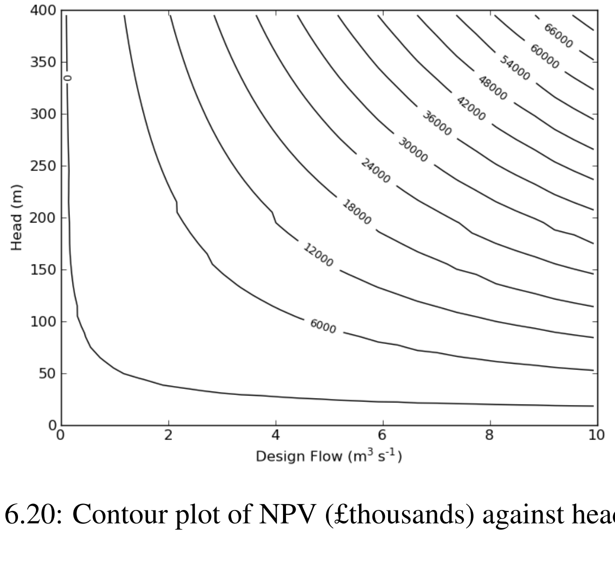


Figure 6.20: Contour plot of NPV (£thousands) against head and flow

critical region. Costs can be seen to drop more rapidly with change in head than change in flow, showing that even very low flow sites can be economic if the head is high enough.

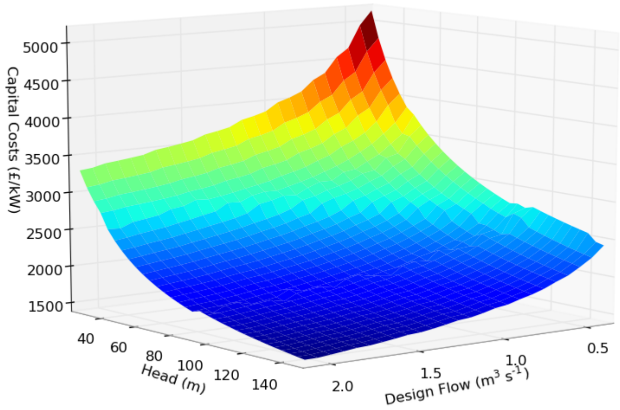


Figure 6.21: Cost surface for narrow range of head and flow in region occupied by marginal sites

Capital costs are found to be below approximately 2500 £/kW for schemes with positive NPV (at 10 % discount rate and slope of 1 in 10), this corresponds with the simple analysis carried out in section 6.5.5 which showed that capital costs below 2300 £/kW were required for a scheme to have a positive NPV. The costing method is shown to behave in a rational and consistent way, with clear economies of scale favouring increase in head over flow evident.

6.6 Example Results

An example application of the hydro search is shown for the Fionn Ghleann catchment located in Glen Falloch, one of a number of sites identified in this area. This example has been located with a discount rate of 10% and at a discount rate of 15% the site is found to be uneconomic.

Figure 6.22 shows the powerhouse and intake (represented as triangles) together with the penstock route which extends over 2262 m. The identified site has a gross head of 214.6 m and a design flow set at Q_{20} of 1.35 m^{3}s^{-1} giving a design power of 2.14 MW. The design parameters for the site are shown in Table 6.3. The values calculated for each cost category are shown in Table 6.4 and the economic performance of the site is shown in Table 6.5.

The corresponding power curve produced by equation 6.31 is shown in figure 6.23, this shows

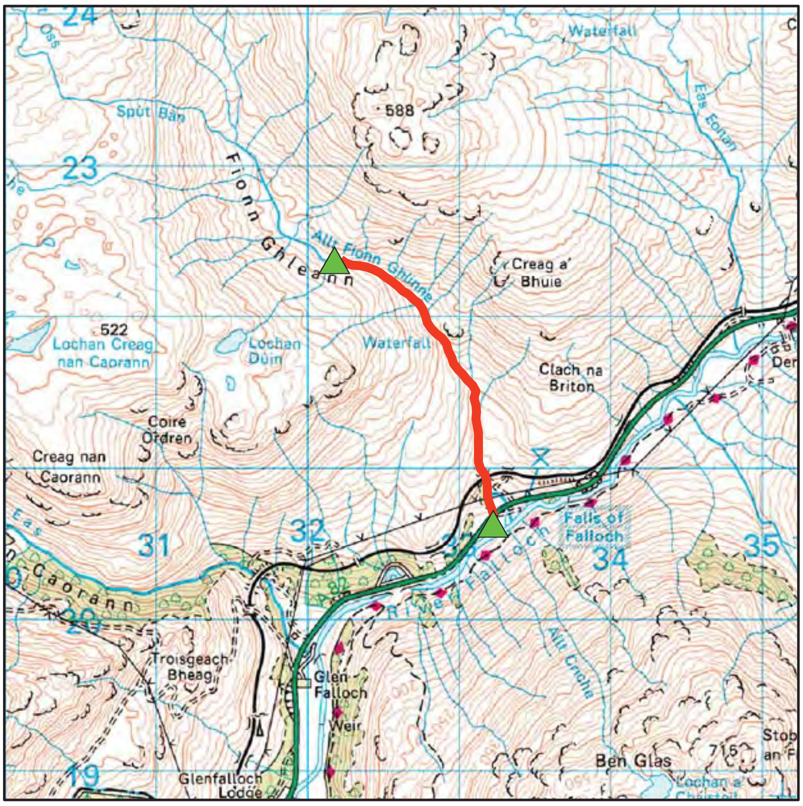


Figure 6.22: Fionn Ghleann hydrosite layout

the output power falling from maximum production at design flow Q_d as available flow falls and turbine efficiency declines.

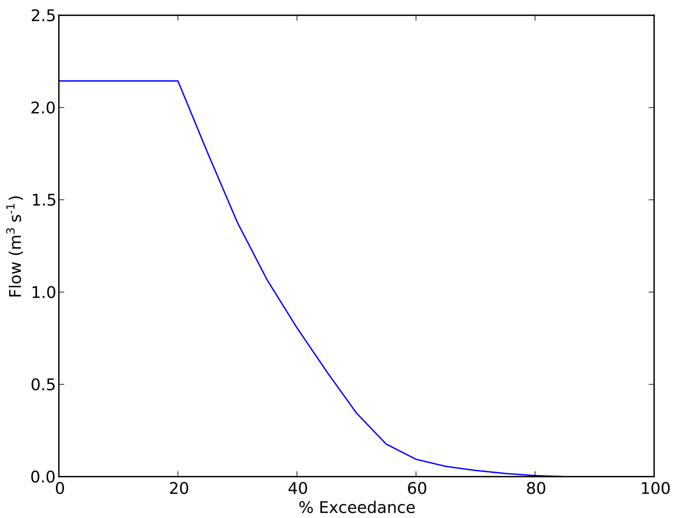


Figure 6.23: Fionn Ghleann hydrosite power curve

Power time series was generated for the period 1961-2000. A sample of this for 1961 is shown in Figure 6.24. This was then averaged by month and, based upon the scheme design power, the average monthly capacity factor for the 40 year period was calculated as shown in Figure 6.25. The capacity factor takes the expected pattern of maximum production occurring during the winter months with a significant reduction occurring during the summer months.

The site is shown to be economic despite significant grid connection costs for the required 10.5 km transmission line. LEC is somewhat higher than the values identified by the IEA in section 6.5.3. After grid connection the cost of penstock makes up the largest proportion of the total cost. If the original RETScreen steel penstock costing method had been employed this cost would be at least twice as large, making the site appear uneconomic.

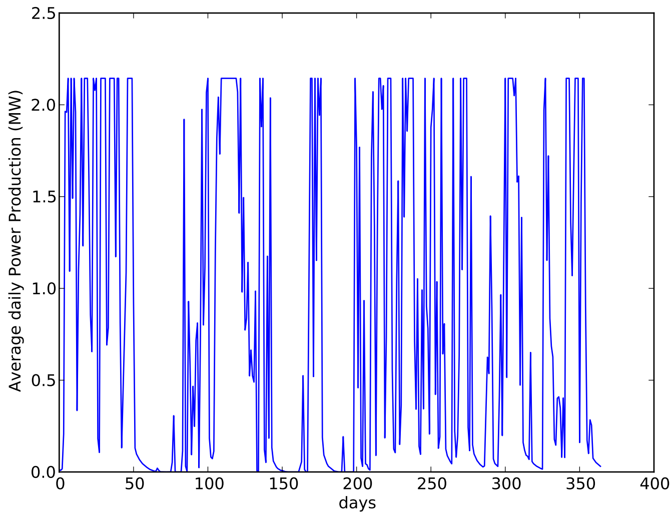


Figure 6.24: Time series of power production for 1961

6.7 Impoundment Search Method

The search method was extended to cater for single impoundment schemes. The procedure for searching for impoundment sites begins with the process used for ROR. When a suitable ROR site is found a test is made to determine whether a suitable dam can be constructed at the site. As impoundment sites are dispatchable it is possible to limit operation to periods of peak demand, when electricity prices are higher. Operating at a reduced capacity factor allows the installed capacity to be increased compared to the ROR of case. This makes sense if the extra revenue gained from peak operation is large enough to enable additional investment in a dam

Design Parameter	Value
Design Flow Q_d (m^3s^{-1})	1.35
Design Flow (% of FDC)	Q_{15}
Design Power (MW)	2.14
Gross Head (m)	214.6
Net Head (m)	200.84
Penstock Length (m)	2262
Penstock Diameter (m)	1.2
Access Road Length (km)	2.3
Transmission Line Distance (km)	10.5
Slope	1 in 10.54
Turbine Type	Pelton

Table 6.3: Fionn Ghleann site design parameters

Item	Cost £	% of total
Feasability Study	128,353	3.1
Development	136,454	3.3
Engineering	135,970	3.3
Turbine & Generator	468,502	11.3
Turbine & Generator Installation	70,275	1.7
Access Road	64,293	1.6
Grid Connection	1,014,281	24.5
Substation and Transformer	23,305	0.6
Substation and Transformer Installation	3,495	0.1
Civil Structures	591,328	14.3
Penstock	872,394	21.1
Penstock Installation	167,509	4.0
Miscellaneous	463,227	11.2
Total	**4,139,391**	-

Table 6.4: Fionn Ghleann cost estimation

Performance Metric	Value
Annual Energy Production (MWh)	7305
Capacity Factor	0.39
Discount Rate (%)	10
Electricity Price Received (£/MWh)	94
Total Costs (£)	4,139,391
Total Costs (£/kW)	1930
Total Discounted Revenue (£)	5,105,613
NPV (£)	966,221
LEC (£/MWh)	73.75
DPP (years)	14

Table 6.5: Fionn Ghleann economic assessment

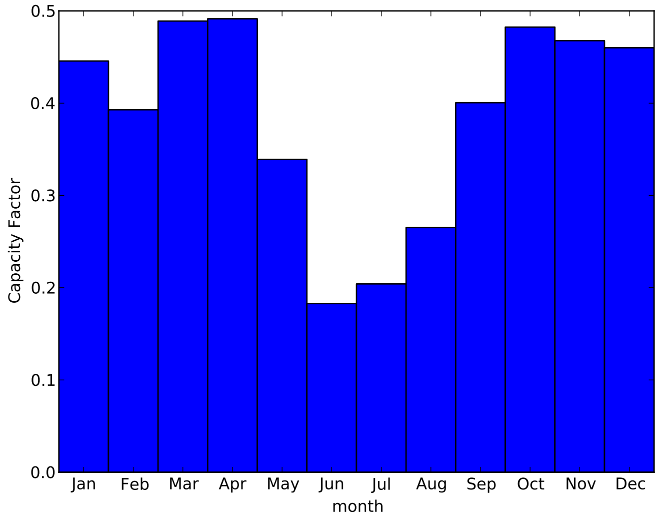


Figure 6.25: Average monthly capacity factor for 1961 - 2000

and plant to be recouped.

To identify suitable locations for dams an algorithm was developed to identify impoundable areas for given dam dimensions. The search utilises the 10 m resolution hydrological data discussed in Chapter 4; the following process is applied at each river cell:

1. Set target dam height to minimum value.
2. Store the DEM elevation value at the river cell as a reference.
3. Extend a dam perpendicularly on both sides of the river cell in pairs of the cardinal directions, east and west, north and south, NW and SE, NE and SW.
4. Extend dam until the difference in DEM elevation at the current dam cell less the reference river elevation ≥ to target height of the dam or dam width limit is reached.
5. If target height is reached calculate dam dimensions based upon height and width.
6. Calculate necessary dam material volume based upon trapezoidal cross-section.
7. If suitable dam identified starting from river cell trace upstream using the D8 flow direction grid until target height is reached. At each cell calculate the difference between the DEM elevation and the target height, multiply this by the cell area to give a stored volume. Repeat until all possible upstream paths have been included up to the target height limit.

Field	Description
GRD10_row	River cell location; used to link to river point data
GRD10_col	River cell location; used to link to river point data
Dam_height	Height of dam structure (m)
Volume	Impoundment volume (m)
Concrete_volume	Volume of concrete required for construction
Width	Dam width (m)
East, West, North, South	Provide length of extension in each direction (m);
NE, SW, NW, SE	used to define dam orientation

Table 6.6: Impoundment data stored in database

8. Record the coordinates of upstream cells prior to target height limit being exceeded to define impoundment area.

9. Sum storage volume identified for cells within target height limit to give total impoundment volume.

10. Increase dam height, giving new target height.

11. Repeat steps 4 to 9 until maximum dam height limit reached.

This method allows a range of impoundment volumes for different dam heights to be developed for each river cell. To limit the search maximum dam width was limited to 1000 m. An initial value of 5 m was used for dam height increasing to 100 m in 5 m increments. The method assumes that a simple trapezoidal gravity dam constructed from roller compacted concrete is used and that suitable impoundment locations will be located in V-shaped valleys (Stevens and Linard, 2002). It is also assumed that a single structure is capable of creating the impoundment, when in fact it may be necessary to use several due to undulating terrain. As such it is necessary to hand check final results for feasibility.

The results from the impoundment search are stored in the search database with reference to each 10 m addressed river point. This allows the impoundment volume, dam dimensions and impoundment area coordinates to be retrieved to allow the scheme assessment to be made. The details of the structure used to store the impoundment data are shown in Table 6.6. A separate list is maintained of coordinates defining resulting inundation areas. These are stored together with the 10 m grid location and dam height allowing a query to be made to return a set of coordinates for a given dam height at a river cell (see Table 6.7).

Once a suitable ROR site is identified the database is queried to determine if a possible im-

Field	Description
GRD10_row	River cell location; used to link to river point data
GRD10_col	River cell location; Used to link to river point data
Dam_height	Dam height (m)
X	Easting defining boundary of inundated area
Y	Northing defining boundary of inundated area

Table 6.7: Inundation area coordinates stored in database

poundment has also been identified. If a site is suitable for impoundment, the identified dam heights achievable for the site are incorporated into the site optimisation procedure detailed earlier in the chapter. Dam cost is included based upon the volume of concrete required to construct the dam (£100/m^3) (PCA, 2010). Different potential design capacities and operating regimes are trialled with the highest in terms of NPV retained. The NPV of the impoundment design is then compared to the ROR case and if it is higher then the site is designated as an impoundment site. A reservoir model is used with maximum storage volume set to the value 'Volume' stored in the database for a particular dam height. River flow time series provide inflows into the reservoir model, while a dispatch rule controls outflow. There are no drawdown constraints, however, a minimum reservoir level of 10% was required to be maintained at all times. The initial reservoir level is set at 50% of the calculated volume. It was found that using the full flow dataset led to significant runtimes therefore the length of flow time series used for assessment was limited to a 5 year period, 1962 to 1967.

A very simple operating regime has been assumed whereby the scheme operates for a set number of half hour periods each day at maximum output. Electricity market data for a three year period was averaged to give the typical variation in prices throughout the day (see Figure 6.26). These are then ranked in descending order. If a scheme operates only during the highest 10 half hourly periods then the price received for each MWh of production is taken as the average of the 10 highest ranked prices. If a scheme operates for the whole day then it simply receives the average electricity price. The average annual energy yield achieved over the 5 year trial period was assumed to represent typical annual yield achieved over the lifetime of the scheme. To account for evaporation from the water body in store average annual energy yield was reduced by 5%.

The increased head available from the dam raising the water level is disregarded. This simplifies calculating the scheme output and discourages the development of high dams to increase scheme head. Only sites with head greater than 100 m were considered to limit impoundment

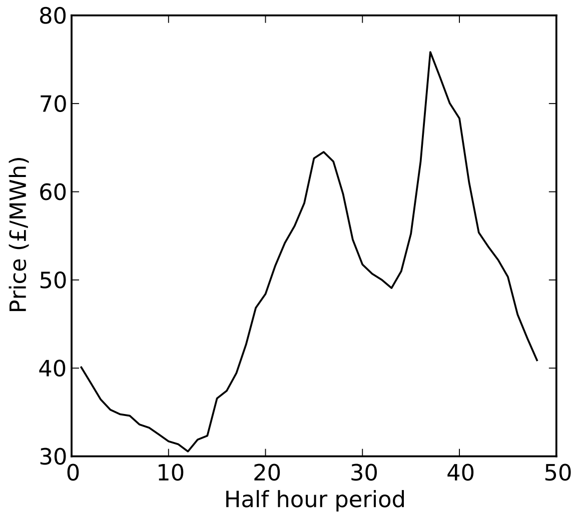


Figure 6.26: Average electricity price at different times of day

development to upland areas less likely to be already used for agriculture, industry or housing.

A test case was developed based upon the proposed RWE Innogy Maldie Burn hydropower scheme located in West Sutherland. This scheme has a design capacity of 4.5 MW and utilises a 30 m long weir that raises the level of Loch an Leathiad Bhuain by 1.5 m. The method was applied to this catchment an initial 2.39 MW ROR site was identified with intake and powerhouse located at similar positions to the proposed scheme. The impoundment search was then performed for this intake power house combination starting with a dam 5 m in height and increasing to a dam elevation of 50 m. Tests were performed using a 5% discount rate. It was found that when allowed to select a design capacity and number of operating hours the method utilised the same design capacity as the ROR case but operate with a greater capacity factor, disregarding the opportunity to generate at peak hours.

To encourage the development of a peaking plant the rate received for peak hour electricity was increased. This was achieved by increasing the 12 half hour periods of peak electricity price using a revenue adjustment factor R_{adj}. Different adjustment factors were trialled to determine the effect on scheme design and are summarised in Table 6.8. It was found that setting R_{adj} to 1.5 for this scheme created the necessary incentive to develop additional capacity. This value was adopted when the impoundment search was performed nation-wide; the ranked electricity price and mean electricity price received are shown in Figure 6.27.

As the peak price is increased using R_{adj} design flow and design power can be seen to in-

Design Parameter	$R_{adj} = 1$	$R_{adj} = 1.5$	$R_{adj} = 10$
Design Flow Q_d (m^3s^{-1})	1	4.3	5.9
Design Power (MW)	2.39	6	8.28
Dam Height (m)	5	5	5
Dam Width (m)	80	80	80
Impoundment Volume (m^3)	11,020,746	11,020,746	11,020,746
Concrete Volume (m^3)	2248	2248	2248
Dam Cost (£)	224,856	224,856	224,856
Daily Operating period (half hours)	46	10	7
Energy Yield (MWh)	10778	11043	11108
Price received (£/MWh)	48.6	98.43	678
NPV (£)	9,700,841	11,966,097	100,399,924
Capacity Factor	0.9	0.21	0.15
Gross Head (m)	178.7	178.7	178.7
Net Head (m)	171.8	168.8	169.4
Penstock Length (m)	2070	2070	2070
Penstock Diameter (m)	1.2	2	2.3
Access Road Length (km)	2	2	2
Transmission Line Distance (km)	9.4	9.4	9.4
Slope	1 in 11.58	1 in 11.58	1 in 11.58
Turbine Type	Francis	Francis	Francis
Catchment Area (km^2)	21.5	21.5	21.5

Table 6.8: Maldie Burn site design parameters

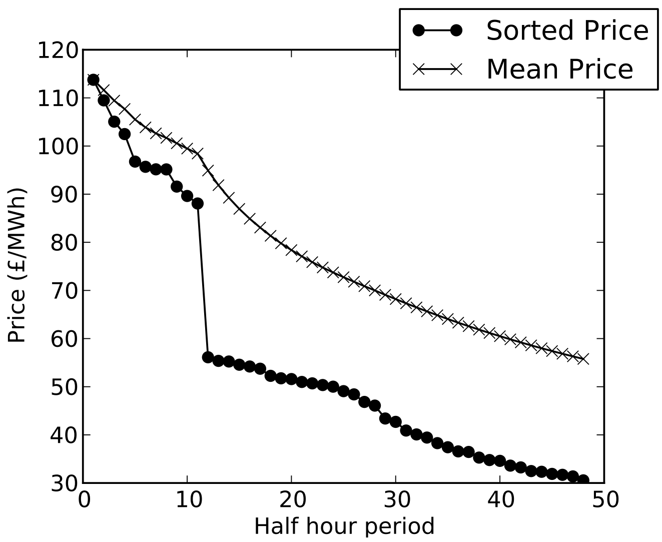


Figure 6.27: Ranked electricity prices and corresponding mean electricity price received for a given operating period when R_{adj} is set to 1.5

crease with a corresponding decrease in operating period and capacity factor. The chosen dam dimensions remain the same despite the increase in peak price, this is reasonable as the 5 m dam offers significant storage compared to the available inflow. A larger dam would create additional storage capacity that would not be filled.

The resulting inundation area from the 5 m dam is illustrated in Figure 6.28. To limit the number of points stored in the database only every 5th point at the edge of the inundation area is recorded. The accuracy of the calculated storage volume was tested against a simple map calculation. The area of the impoundment was calculated using a manual area measurement tool in ArcGIS (equivalent to use of a planimeter) and was found to be 2.2 km^2. This area was then multiplied by the dam height of 5 m giving a volume of 10.5 $\times 10^6$ m^3, giving an error of 5% when compared to the volume calculated by the impoundment algorithm.

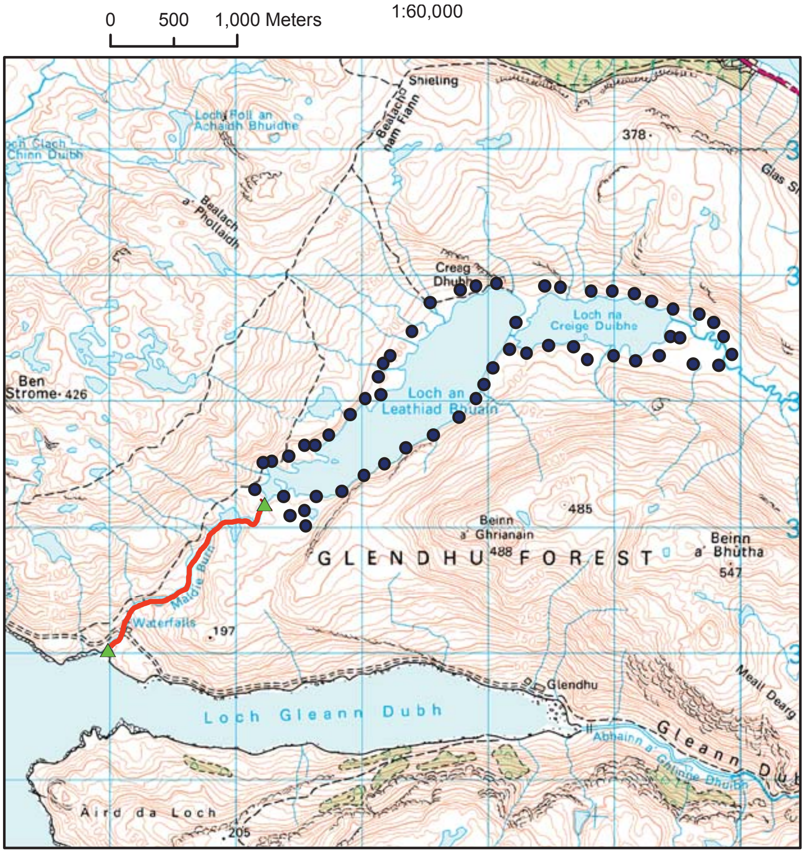


Figure 6.28: Inundation area created by 5 m dam

The operation of the reservoir is shown in Figure 6.29 for the 5 year trial period with R_{adj} set to 1.5. The reservoir level is constant for much of the period of operation, however there is significant drawdown during periods of low flows during summer 1963 and summer 1964.

During these periods of low reservoir levels generation is not maintained as the 10% lower limit is reached.

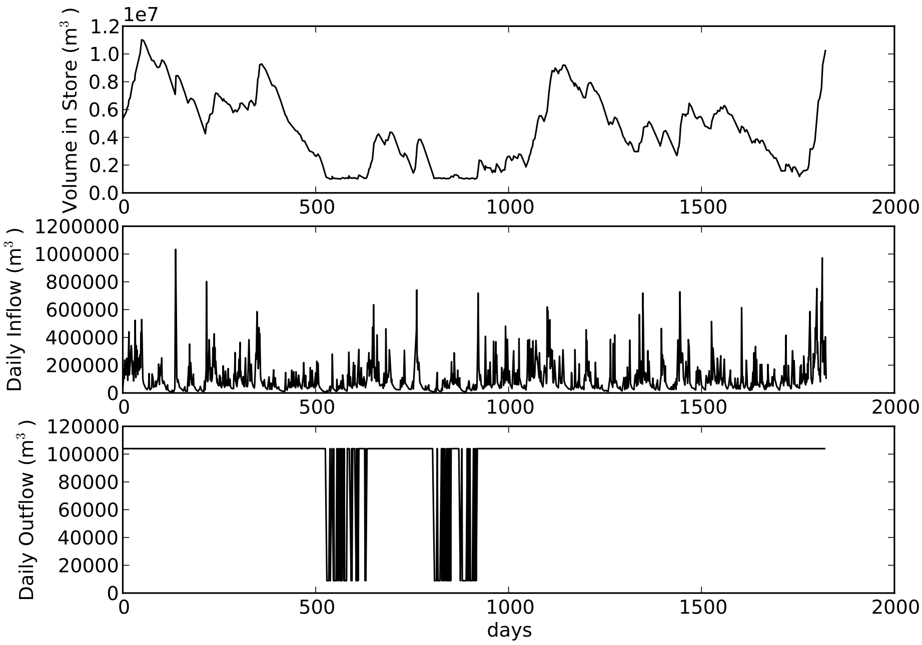


Figure 6.29: Maldie Burn Reservoir inflow, outflow and volume

6.8 Chapter Summary

A method has been developed that is able to locate suitable sites for economic small run-of-river hydroplant utilising flows developed using the G2G hydrological model. Local site optimisation is performed identifying optimal design flow and penstock diameter. The method has been demonstrated for a location in the Glen Falloch catchment, illustrating the detailed costing and design details that can be produced. The method has also been further extended to enable impoundment schemes to be identified. The availability of time-series flow data allows the reservoir to be correctly sized to the resource and a simple operating rule to be optimised. The next chapter will provide results of results from the hydro search when applied nationally.

7
Results

"And God said, 'Let there be light' and there was light, but the Electricity Board said He would have to wait until Thursday to be connected."

– Spike Milligan

7.1 Introduction

This chapter presents the results produced by the hydropower search method in terms of the aggregate installed capacity and energy yield for Scotland and also the spatial distribution of identified hydropower schemes. Aggregate daily generation from the run-of-river schemes identified at 10 % discount rate is hindcast for the period 1961 to 2005 allowing the temporal distribution of the resource to be investigated. The necessary error checking and quality control undertaken is discussed together with the identified sources of error. The results are compared to those from other studies with key differences highlighted. Results produced from simulating several hydropower schemes under potential future climates are presented.

7.2 Application of the Hydro Search Nationwide

The hydro search method was applied to the whole of Scotland. 3 main scenarios were considered using discount rates of 5%, 10% and 15% to represent different levels of cost of finance and perceived risk. Separate searches were performed for impoundment and ROR schemes with the results presented separately as the development of impoundment schemes is less likely due to environmental concerns.

Recent (2012) changes in ROC allocation to hydro-schemes have not been included in this assessment, neither have proposed changes in FIT rates for sub-5 MW projects (see Table 7.2). A single ROC value of £49 and fixed electricity price of £45/MWh have been assumed providing an income of £94/MWh. While this does not precisely follow the current (rapidly changing) subsidy regime for hydropower it does consider it in the same terms as received by other renewable generation types, notably wind.

Tariff band (kW)	Proposed tariffs from October 2012
≤ 15	£219 /MWh
> 15 ≤ 100	£197 /MWh
>100 ≤ 2000	£121 /MWh
>2000 to ≤ 5000	£45 /MWh

Table 7.1: FIT values for hydropower (Ofgem, 2012)

Ideally additional scenarios would have been created with different levels of subsidy support to represent the impact of potential changes of policy. In addition key costs such as penstock material and grid connection could have been varied to develop understanding of the impact of these upon project viability. Unfortunately there simply was not enough time to carry out the necessary additional runs, data processing and quality checking to allow this.

The price received by impoundment schemes was related to the number of half hours generation per day as discussed in Chapter 6. This reflects the ability of impoundment schemes to dispatch during periods of peak demand with higher available electricity prices. To assess the potential for plant over-sizing, electricity prices were increased by 50%, based upon the attempts to recreate the RWE Innogy Maldie Burn project.

7.3 Run-of-River Results

The hydro-search was run solely for identification of run-of-river sites. The search was performed on each HA using a single Sun workstation. The river and flow database were created on the local drive of the machine and then the search was run on the data for each of the discount rate scenarios. Results were saved from each run as text files containing the location and characteristics of each scheme including intake point, powerhouse location and penstock route.

Initial assessment of the raw results identified 854, 472 and 248 sites at 5%, 10% and 15% discount rates, respectively. These total 1372 MW, 831 MW and 508 MW in capacity. Each identified site was briefly checked for feasibility, with the main criteria for removal being the interference with existing hydropower sites. It was found that the hydro search placed a scheme at the majority of existing hydro sites, adding confidence to the results produced. In addition to those obviously in conflict with existing schemes others were either located downstream of a major scheme or in catchments already abstracted into large schemes. These were removed when identified with the aid of OS survey maps showing the location of dams or weirs in the catchments near to major locations and also with the help of SSE (2005) which provides simple maps showing the tapped catchments. Despite these efforts there may be schemes in conflict with existing sites that have not been fully identified and there will be a number of sites with overstated yield that have not taken into account reduced available flows.

Once the initial screening was carried out an initial assessment of the results was made. When placed in order of descending NPV it was found the best economically performing schemes tended to be low head schemes located in rivers with significant catchment area and hence flow-rate such as the Tummel, Tay and Findhorn. On closer inspection it was found that these sites were identified as having penstock lengths typically less than 100 m with site net heads of 20 m. When the elevation values from the DEM were checked upstream and downstream of the identified site it was found that erroneous estimates of head had been made due to DEM inaccuracies. These erroneous low head sites were removed as part of a second screening process. The number of sites and identified capacity removed during the second screening was much smaller than the previous screening of sites in conflict with existing schemes.

Once the second screening was carried out the remaining results were considered to be technically and economically plausible schemes and treated as the final dataset. These final sites can be found in the Appendix. The volume and installed capacity of identified sites falls dramatically to 898 MW at 694 sites for 5% discount rate, 440 MW at 339 sites for 10% discount rate and 204 MW at 146 sites for 15% discount rate. As summarised in Table 7.2, the results have been grouped into several classes by installed capacity. The vast majority of identified sites lie in the range 1 to 5 MW, with a small number of higher capacity sites identified. Only 2 sites were found below 100 kW and only at a 5% discount rate. The distribution of total capacity installed by size of scheme and discount rate scenario is shown in Figure 7.1. Figure 7.2 shows the cumulative capacity for different levels of scheme levelised electricity costs (LEC).

The costs of schemes was found to be in general agreement with the figures from DECC discussed in Chapter 2. As Table 7.3 shows, the mean and maximum figures correspond, the minimum figures are somewhat lower and the high value of £4152/kW for schemes under 1 MW in size is roughly half of that reported by DECC. The costs generally increase as the discount rate falls as greater capital expenditure can be recovered.

	5% Discount Rate		
Scheme Size	**No. of schemes**	**Power (MW)**	**Energy (GWh)**
< 100 kW	2	0.16	0.917
100 kW to 500 kW	198	57	258
500 kW to 1 MW	181	130	519
1 MW to 5 MW	297	591	2034
5 MW to 10 MW	14	95	285
> 10 MW	2	25	67
Total	**694**	**898**	**3164**
	10% Discount Rate		
Scheme Size	**No. of schemes**	**Power (MW)**	**Energy (GWh)**
< 100 kW	0	0	0
100 kW to 500 kW	96	29	132.9
500 kW to 1 MW	88	65	285.2
1 MW to 5 MW	148	295	1161
5 MW to 10 MW	7	51	170.3
> 10 MW	0	0	0
Total	**339**	**439.6**	**1749.4**
	15% Discount Rate		
Scheme Size	**No. of schemes**	**Power (MW)**	**Energy (GWh)**
< 100 kW	0	0	0
100 kW to 500 kW	38	12.4	59.9
500 kW to 1 MW	41	28.6	129.8
1 MW to 5 MW	63	135	577.7
5 MW to 10 MW	4	27.9	101.88
> 10 MW	0	0	0
Total	**146**	**203.9**	**869.28**

Table 7.2: Summary of Scotland-wide ROR results (post screening)

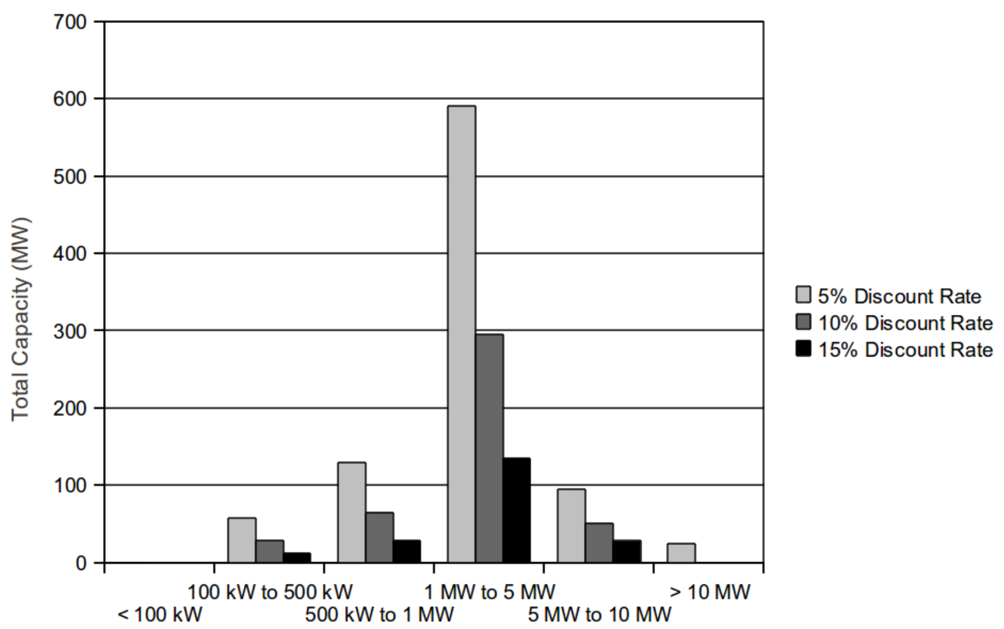


Figure 7.1: Installed capacity at different discount rates

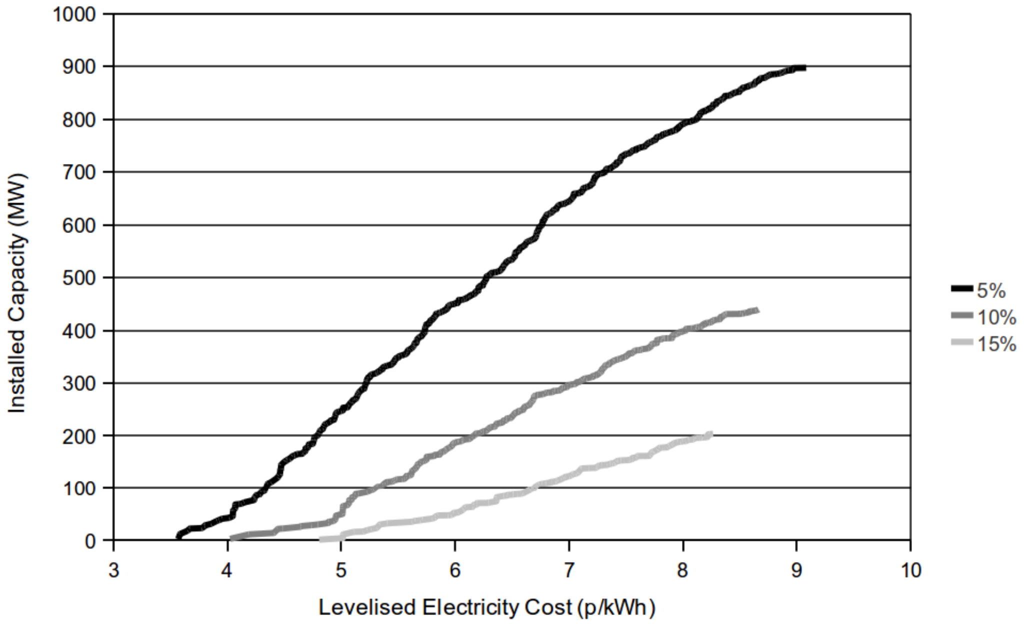


Figure 7.2: Range of levelised electricity costs

Installed Costs (£000s/MW)	< 1 MW	1-5 MW	> 5MW
High	4152	3959	1554
Median	2545	2041	1308
Low	1367	938	968

Table 7.3: Hydropower installed costs at 10% discount rate

Schemes are found for the most part in the Highland region, which is unsurprising given that this is the region with greatest suitability for hydropower. Identified schemes tend to be clustered around existing 33 kV lines; this is especially noticeable for the 10% and 15% discount factor scenarios showing that the financial feasibility of a site is strongly influenced by the distance it lies from a suitable grid connection point. This is clearly shown in the illustrations of the nation-wide spatial distribution of identified schemes provided in Figures 7.3, 7.4 and 7.5.

7.4 Comparison with Other Studies

The run-of-river results compare well with other studies undertaken. It is interesting that the magnitudes of total capacity of the different discount rate scenarios broadly correspond with the upper and lower limits identified by previous studies (1000 MW and 224 MW). When compared to the results of the Nick Forrest Associates (NFA) (Nick Forrest Associates, 2008) study there are some notable similarities and differences. Their results are for an 8% discount rate, therefore the closest results from this work are for the 10% scenario.

NFA found a total of 657 MW from 1019 schemes providing 2.77 TWh of energy per year. Here a far lower number of schemes have been identified overall with for the 10% discount rate scenario, some 339, producing 1.7 TWh from 440 MW of capacity. Figure 7.6 compares the results from this work with those found for the NFA 8% discount rate scenario. The amount of generation identified in the 1 MW to 5 MW and 5 MW to 10 MW scheme size classifications is similar. Major differences lie, however, with schemes of smaller size where the NFA report identifies an additional 130 MW of sites between 500 kW and 1 MW in size and 175 MW more schemes between 100 kW and 1 MW in size.

Given that the NFA approach considered connection to assumed 11 kV lines located in habitation (defined as the centre of a postcode), it is likely that smaller schemes were able to connect locally at this voltage, rather than making an extended connection to a distant 33 kV line. The cost of connection is effectively an overhead, the recovery of which must be made from profitable operation of the hydropower scheme. Therefore to allow the cost of a lengthy 33 kV connection to be fully recovered a scheme must be above a certain size. Other reasons for the differences in findings are likely due to the Black and Veatch supplied cost estimates producing lower costs for smaller schemes than the RETScreen costing method. A further potential reason is that here the minimum distance for searching the river reach was 50 m. It was understood

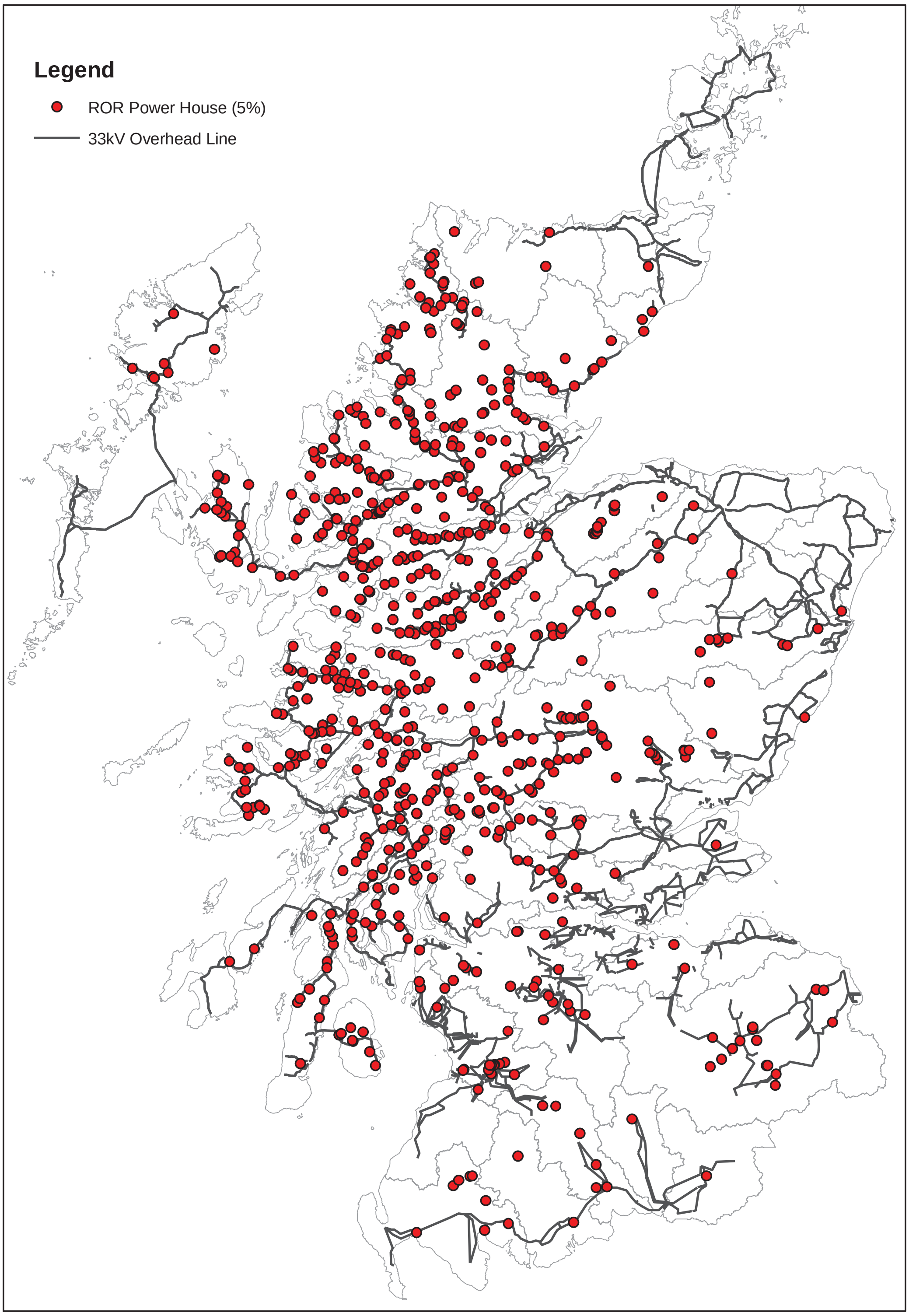


Figure 7.3: Run-of-river sites identified at 5% discount rate

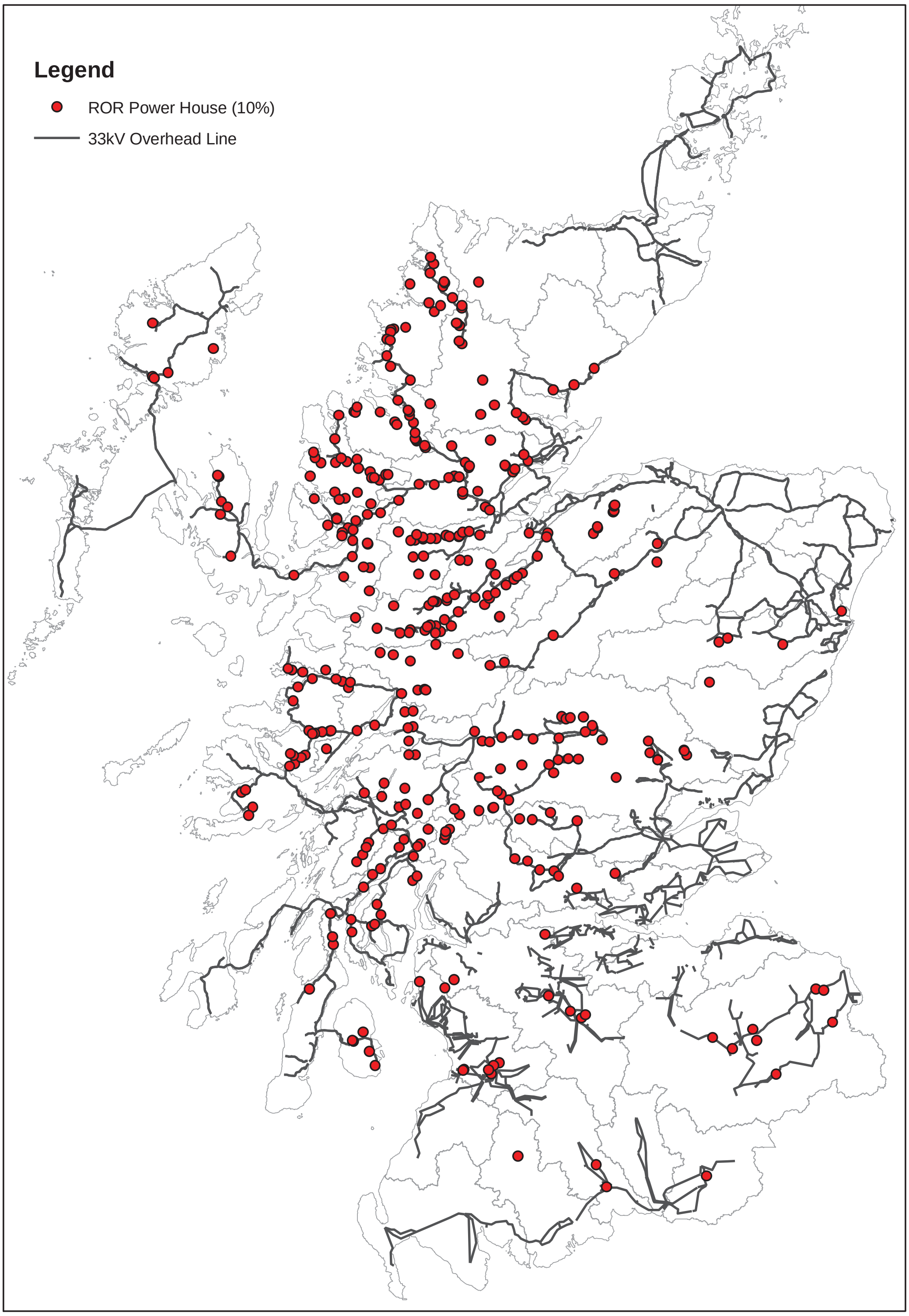


Figure 7.4: Run-of-river sites identified at 10% discount rate

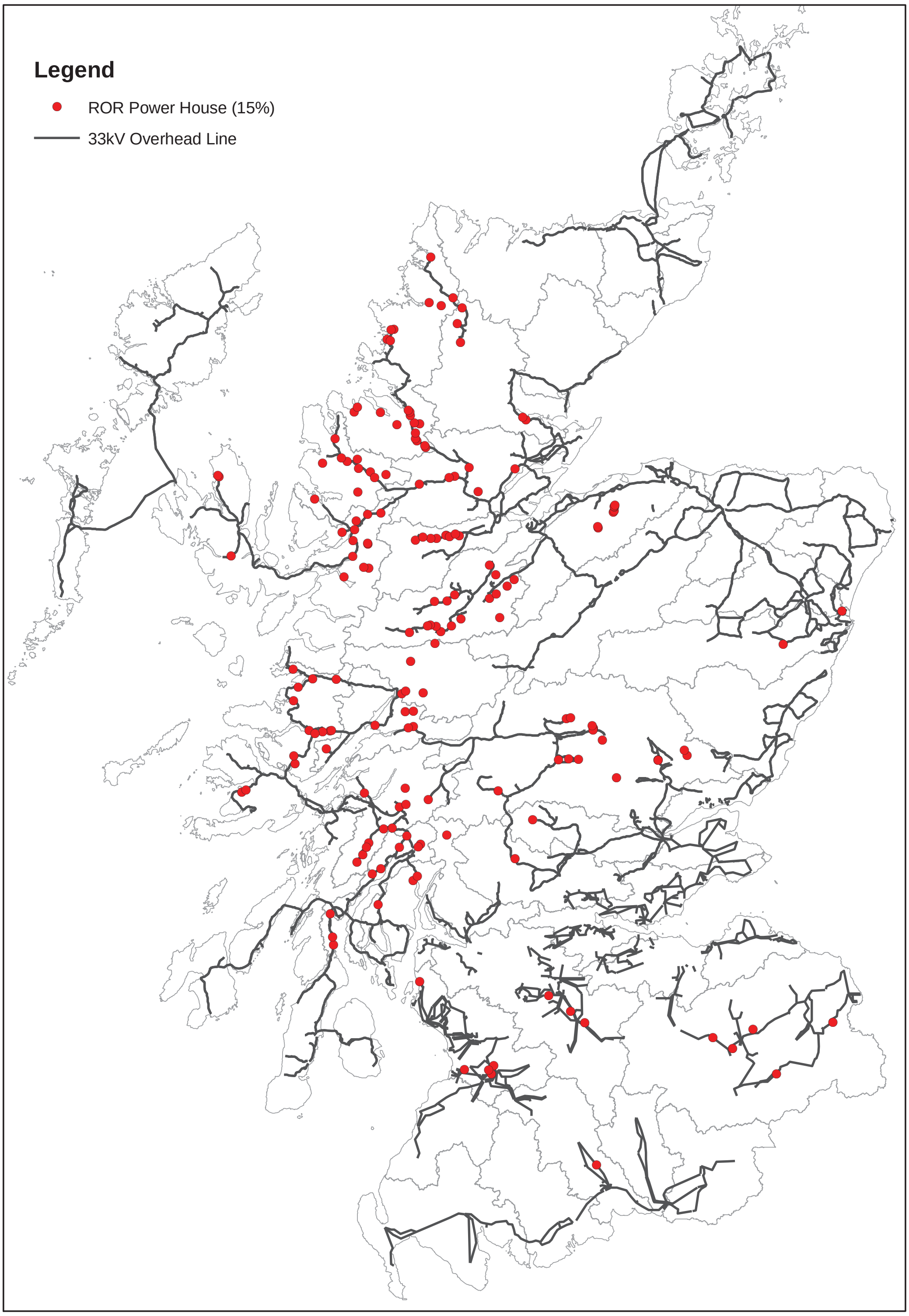


Figure 7.5: Run-of-river sites identified at 15% discount rate

that NFA did not restrict this and, as a result, some smaller schemes may have been excluded.

The Salford Civil Engineering Ltd (1989) study identified a greater number of schemes in the < 100 kW and 100 to 500 kW classifications (231 and 475 respectively) and fewer at higher power. This is likely due to differences in cost and revenue assumptions. These findings are included in Figure 7.6 for comparison.

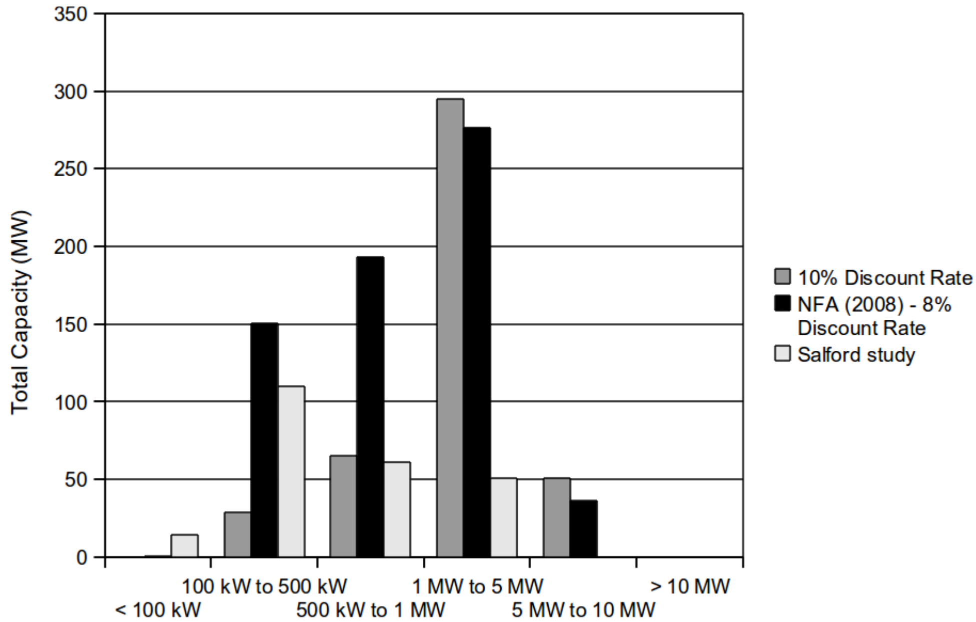


Figure 7.6: Comparison of identified sites with other studies

7.4.1 Detailed Run-of-River Findings

The Western Highlands were found to have the best potential for new run-of-river hydro, due to the wet steep geography and limited existing hydropower development. A more detailed set of maps in Figures 7.7, 7.8 and 7.9 show the spatial distribution of identified sites. There is generally good agreement between the discount rate scenarios in the sense that sites identified at 15% discount rate are re-produced at lower discount rates. When this occurs the penstock will typically be extended or the design capacity increased in size.

7.5 Impoundment Sites

A separate and smaller scale search for high head impoundment based schemes was made with a discount rate of 5% using the impoundment search method discussed in Chapter 6. These

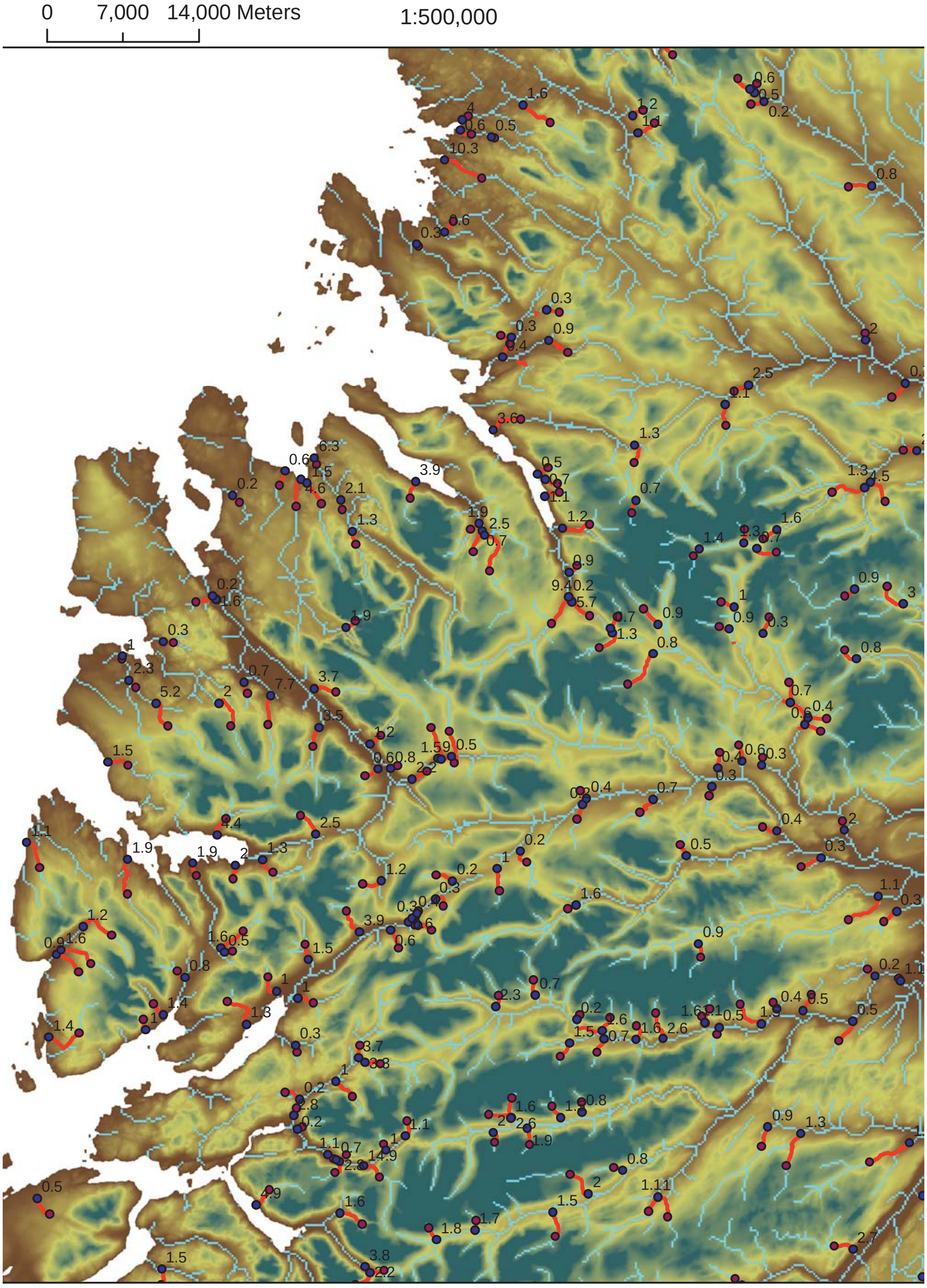


Figure 7.7: Run-of-river sites at 5% discount rate. Capacity labelled in MW, powerhouse by blue circles, intakes by red circles and penstocks by red line.

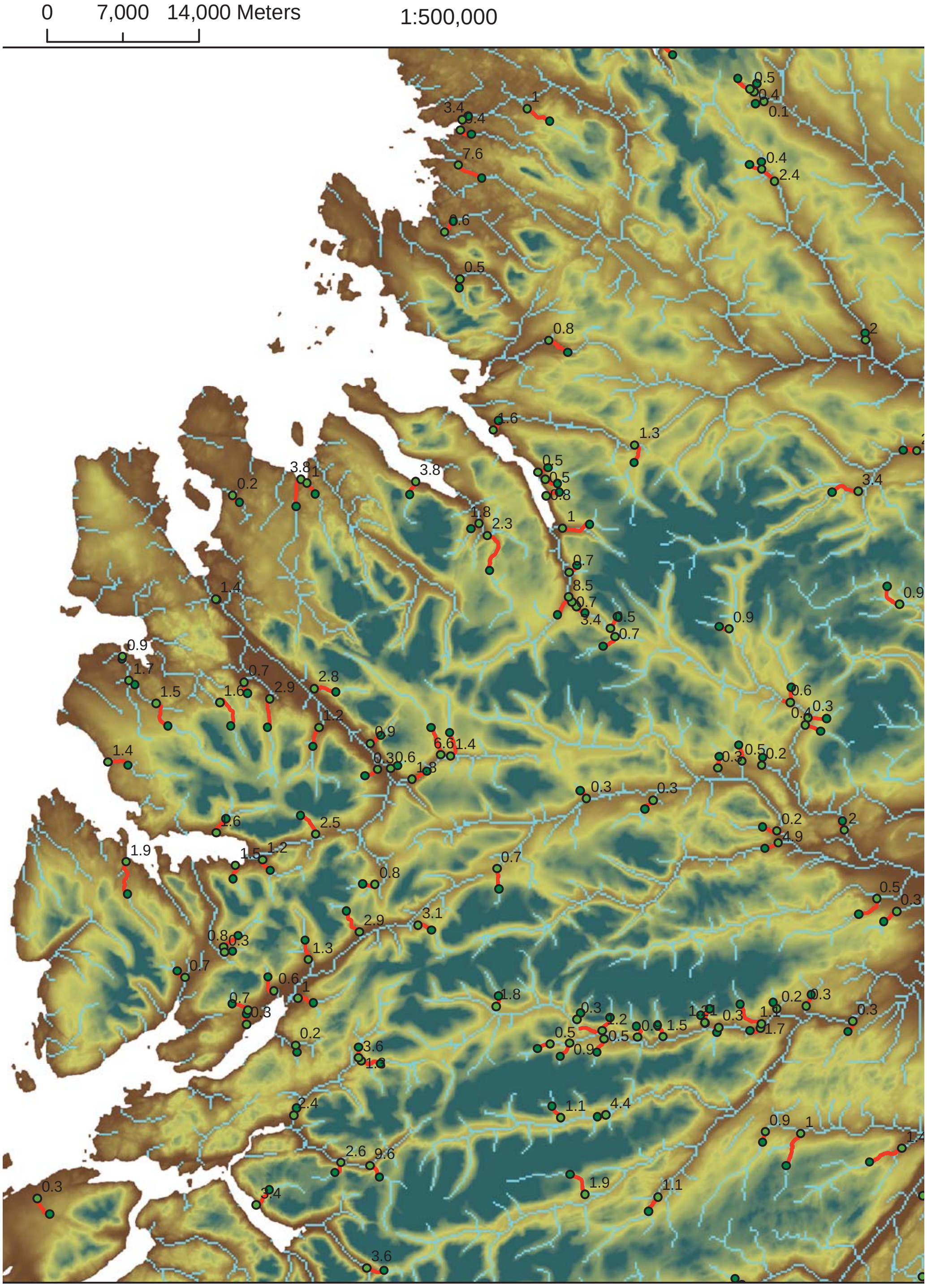


Figure 7.8: Run-of-river sites at 10% discount rate. Capacity labelled in MW, powerhouse by blue circles, intakes by red circles and penstocks by red line.

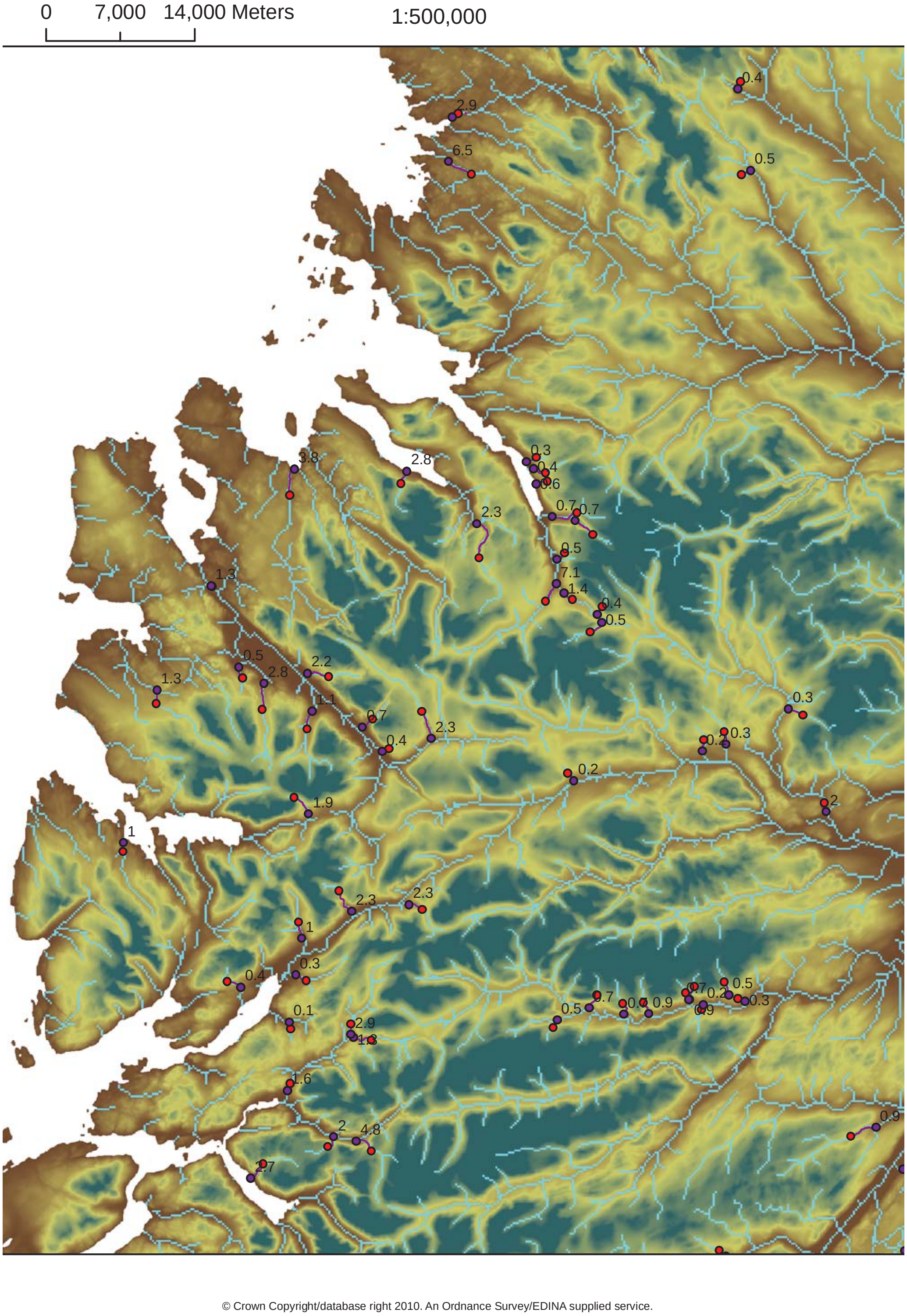


Figure 7.9: Run-of-river sites at 15% discount rates. Capacity labelled in MW, powerhouse by blue circles, intakes by red circles and penstocks by red line.

were assessed for basic feasibility using the same process as for run-of-river sites but with added attention paid to the creation of reservoirs and subsequent inundated areas. Schemes were rejected if they would impact dwellings or any other built up locations or productive land, generally forestry. A similar process of screening was carried out.

A number of feasible schemes were found. Table 7.4 provides an overview of the identified sites at different scales and Figure 7.11 an indication of their spatial distribution. These final sites can be found in the Appendix. Like the ROR findings the majority of identified sites are located in the Highland region with a significant proportion including the most viable sites located in the North West Highlands. As the search method relied upon successful initial identification of a viable ROR scheme, the identified sites are located in the position of good ROR sites. As such the 108 MW of impoundment sites identified cannot simply be added to the the total identified ROR capacity at 5% discount rate.

The sites were not all developed as over-sized peaking plant as had been expected. Rather the search algorithm tended to undersize the plant and use the store to operate at a greater capacity factor. As the marginal cost of increased capital expenditure was not recovered by the increased electricity price received, the scheme was sized to maximise NPV by reducing plant costs (hence smaller installed capacity) and operating at a higher capacity factor. It is expected that inflating peak electricity prices further would lead to the capacity of identified impoundment sites being increased, as was found with the Maldie Burn test case.

Furthermore the use of a more realistic mode of operation might deliver different results. One option would be for the scheme operator to set a minimum price threshold for operation that could vary depending on season and market conditions, market prices would then act as a signal for operation. Further optimisation could then be performed to maximise revenue using historic time series of market prices, available inflows, operating rules and constraints to maximise revenue.

	5% Discount Rate		
Scheme Size	**No. of schemes**	**Power (MW)**	**Energy (GWh)**
500 kW to 1 MW	3	2.3	11.5
1 MW to 5 MW	31	79	311.8
5 MW to 10 MW	2	13	56
> 10 MW	1	13.8	28.9
Total	**38**	**108**	**408**

Table 7.4: Summary of Scotland-wide impoundment search results

Several of the identified impoundment sites were found to have substantial storage potential,

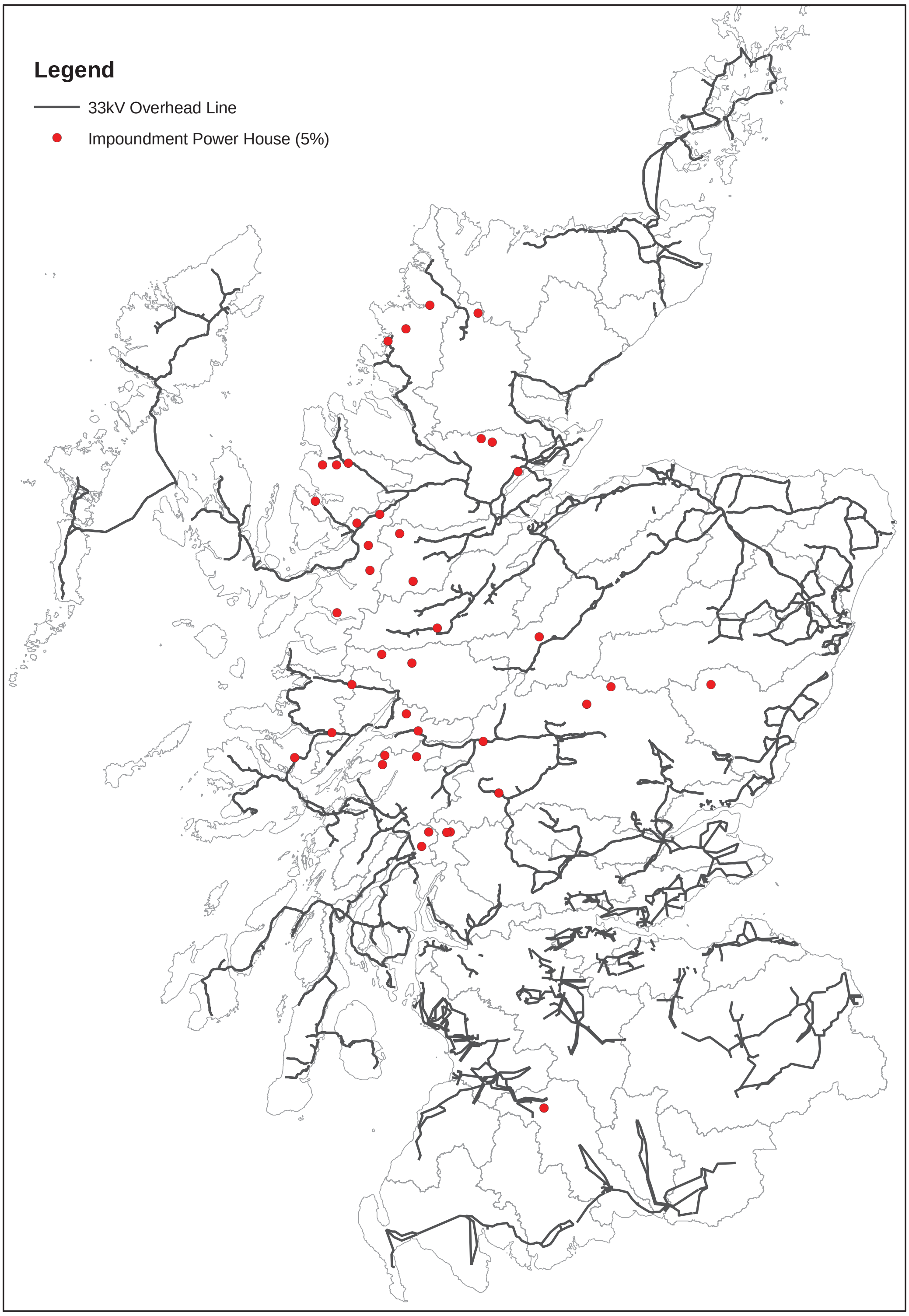


Figure 7.10: Identified impoundment sites at 5% discount rate.

notably Falls of Kirkaig offers a significant opportunity for development of an impoundment scheme. Again a number were found in the North West, as shown in Figure 7.11 where the number label refers to the scheme details in Table 7.5. Given that the search method tended to produce solutions with high capacity factors, the capacity size of these schemes could potentially be increased if the simulated market prices were higher.

River	**Power (MW)**	**Dam Height (m)**	**NPV M£**	**Energy (MWh)**	**Capacity Factor**	**Ref. to Fig. 7.11**
Abhainn a' Gharbh-Choire	1.1	5	6.5	8364	0.83	1
Abhainn Brigh Horrisdale	3.1	5	11.0	13353	0.48	2
Abhainn Dubh	1.3	10	7.0	10237	0.84	3
Allt a' Ghlomaich	4.5	15	21.5	22236	0.56	4
Allt an Tiaghaich	1.07	10	4.4	6650	0.70	5
Maldie Burn	5.9	5	12.0	11044	0.21	6
Allt Coire Shaile	3.6	10	5.3	6314	0.20	7
Allt Dearg	3.4	10	10.1	11794	0.39	8
Alltan Odhar	1.15	5	4.0	6058	0.60	9
Loch Kirkaig	7.0	15	44.8	44947	0.73	10
Loch na Fideil	4.3	5	19.5	18393	0.48	11
Loch Pollain Buidhe	1.0	5	3.5	6175	0.66	12
Lochan Annie	3.71	20	10.7	12608	0.39	13

Table 7.5: Impoundment sites identified in North West Highlands

7.6 Temporal Assessment of the Resource

The previous section detailed the findings of ROR and impoundment schemes. Further analysis has been made of the ROR findings by investigating the aggregate daily output of the 440 MW of run-of-river schemes found for the 10% discount rate. The identified sites were modelled using the turbine model presented in the previous chapter for the period 1962 to 2004. 1961 has been omitted as this formed part of the spin-up data used by the G2G model to initialise moisture stores.

The turbine daily generation for all schemes was summed to give aggregate generation. Figure 7.12 shows the complete aggregate time series for 1990. It shows considerable fluctuations across the year will high generation levels in winter and early spring and some very low production in summer. Figure 7.13 shows the contribution made by schemes in each individual HA during September and October 1990 (the period between day number 250 and 300 in Figure 7.12. This illustrates that while there is significant correlation between different HAs there are differences in phase and magnitude shifts between the time series that introduce a smoothing

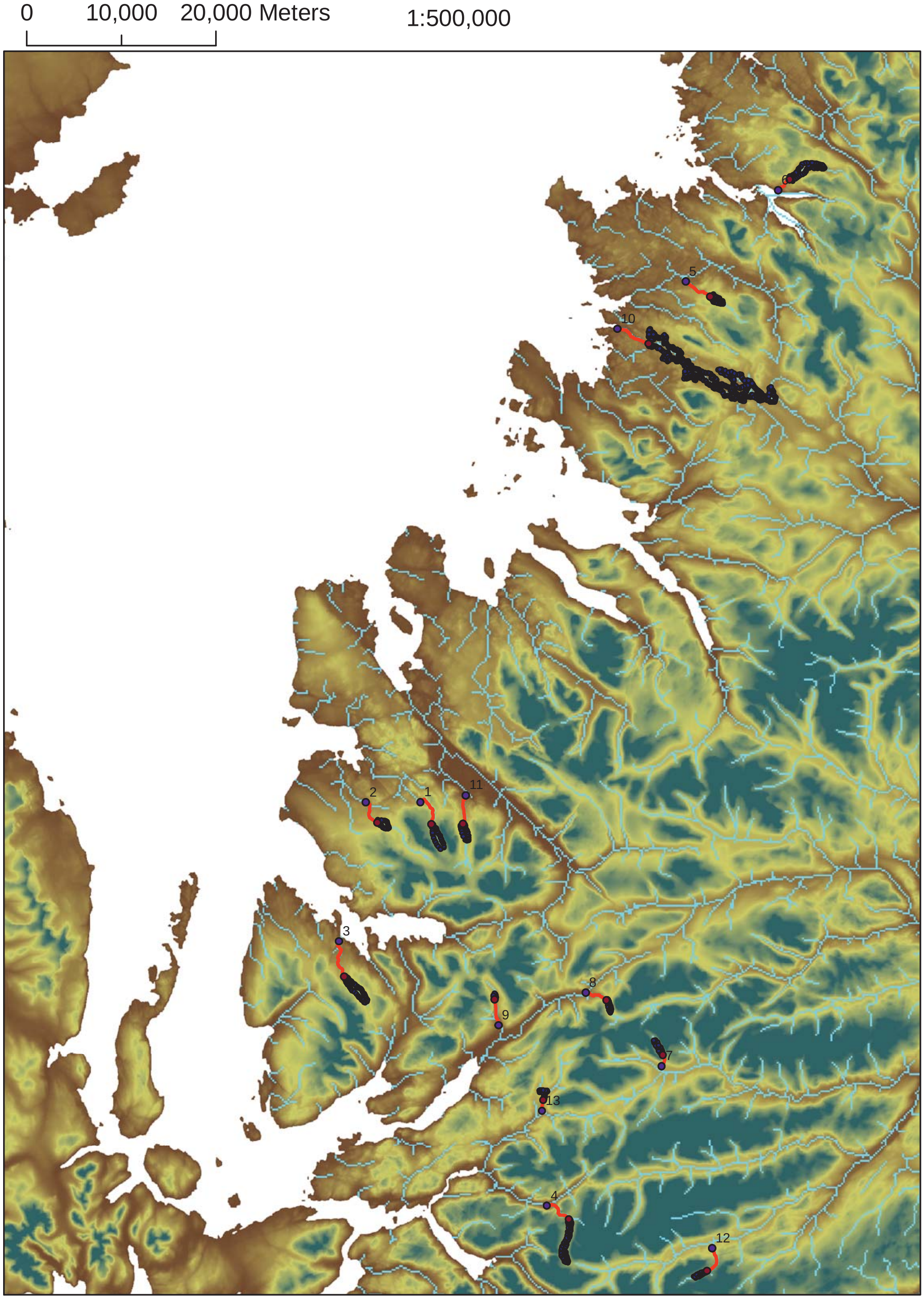


Figure 7.11: Impoundment sites identified in North West Highlands. Numbering refers to site details in Table 7.5, powerhouse indicated by blue circles, intakes by red circles, penstocks by red line and extent of reservoir by black line.

effect. There are significant periods during the winter when production is sustained over consecutive days. Monthly average yield has been calculated across the period 1962 to 2004 using the daily aggregate generation data. This has enabled the average monthly variation in yield to be determined with Figure 7.14 showing strong seasonal production variability ranging from capacity factors of around 57% in December to below 20% in June. The impact of the snow melt model can be seen in the Figure as March has a higher level of production than February. The annual total energy production was calculated over the period of the hindcast (see Figure 7.15) illustrating the wide range of production between years: the range of annual capacity factors span 33 to 55%.

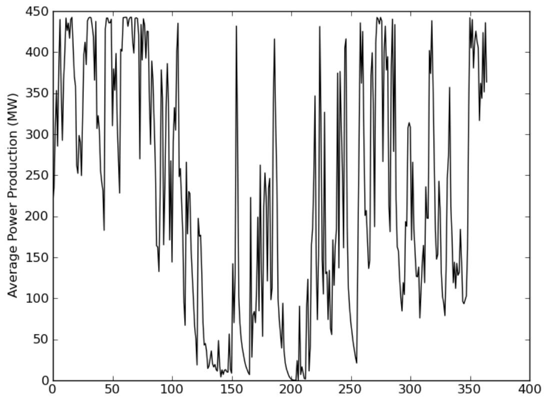


Figure 7.12: Daily aggregate ROR generation for 1990

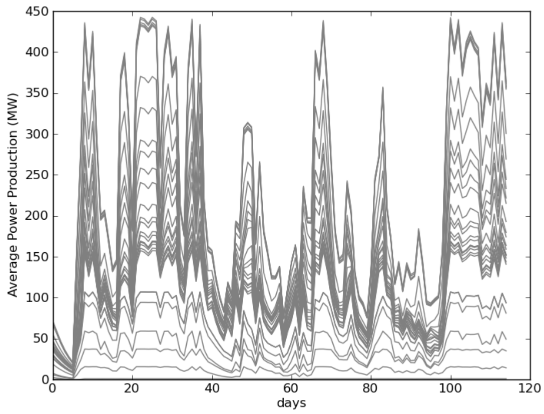


Figure 7.13: Individual ROR generation summed by HA to give aggregate for September to year end 1990

7.7 Climate Change Impacts

To investigate the impact of climate change upon Scotland's hydropower resource the UKCP09 Weather Generator described in Chapter 2 was used to simulate future climates for five catch-

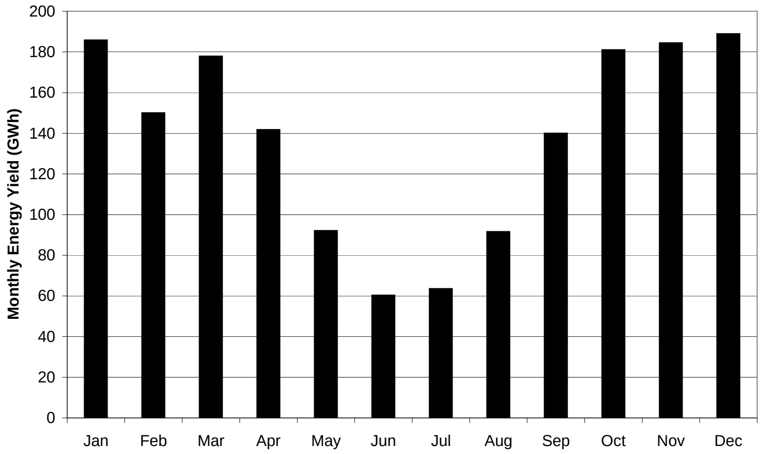


Figure 7.14: Average monthly yield

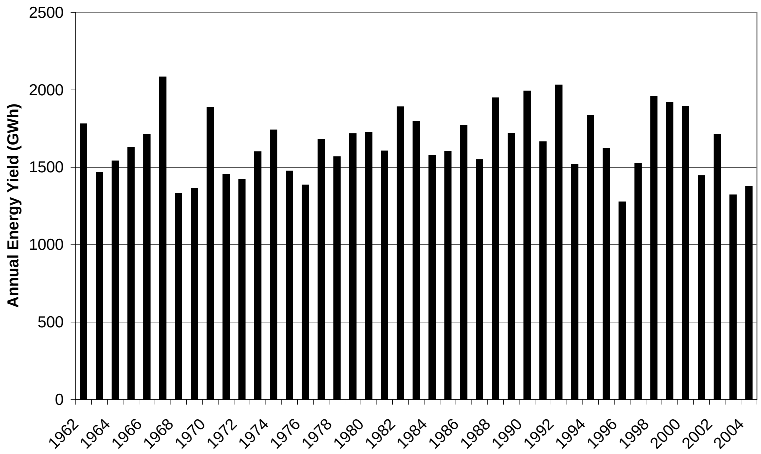


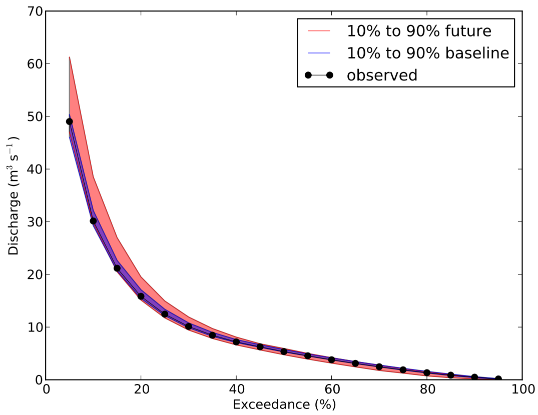
Figure 7.15: Annual energy yield over hindcast

ments: Oykel at Easter Turnaig (3003), Ewe at Poolewe (94001), Cree at Newton Stewart (81002), Irvine at Shewalton (83005) and Deveron at Muiresk (9002). These catchments were selected because they were modelled with low water balance error, achieved good reproduction of the observed FDC and were distributed across the country. Individual catchment calibrations developed using the SCE-UA procedure were used rather than the regional parameterisation to increase model confidence. A hypothetical hydropower scheme was placed within each catchment consisting of a single Francis turbine with 100 m of head. Scheme design flow was selected as Q_{40} using a FDC generated from the baseline flow data for the period 1961-1990.

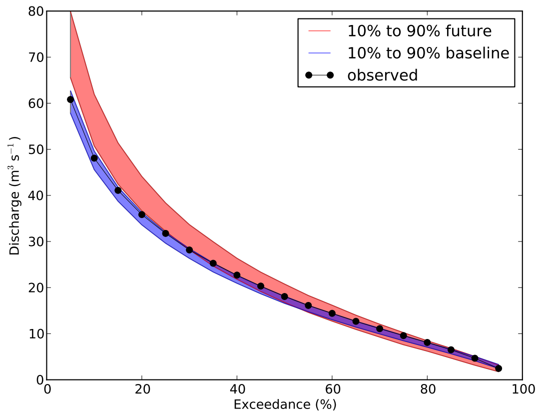
The Weather Generator allows selection of multiple 5 km cells within the model domain to enable weather for an area composed of multiple cells to be synthesised. The Weather Generator is not able to produce spatially correlated results between grid cells, however, the user has the option to select a number of grid cells producing weather time series based upon statistical properties of all grid cells in the area. UKCP09 guidance recommends against using cells with largely differing terrain in a WG run as this can produce results that are not representative of the area. This was encountered during initial trials using WG data, particularly in areas of complex terrain in the Scottish Highlands. It was found that selecting squares covering a catchment area led to rainfall and evapotranspiration that did not agree with catchment water balance and that selecting a single grid square within the catchment under study that had similar annual average rainfall to the WG baseline produced better results. This could be considered analogous to using data from a single weather station located within a catchment to force a hydrological model and because of this large catchments were not chosen.

The 1 km^2 resolution G2G model was run using the 100 sets of future and baseline rainfall and evapotranspiration data to develop 30 year flow time series for both periods. The future data generated using the medium emissions scenario for the period 2040 to 2069. To make use of the snowmelt model it would be necessary to develop elevation corrected estimates of mean temperature. As the available temperature data from the Weather Generator was essentially at a fixed point it was decided to omit the snowmelt model during the climate change investigation.

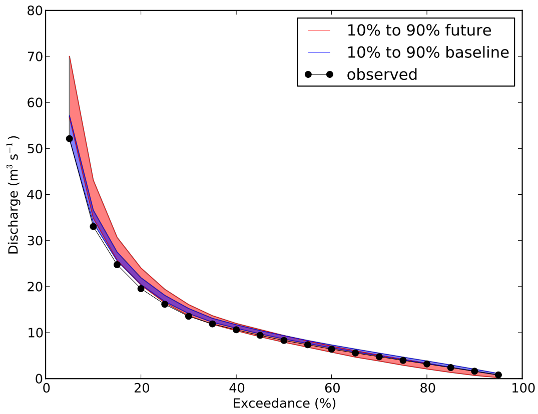
The UKCP09 Weather Generator makes use of change factors developed from probabilistic climate scenario. It is recommended that a minimum of 100 sets of future and baseline synthetic time series are used for modelling to capture the range of uncertainty in the climate predictions. The UKCP09 results are represented using a Bayesian approach with 10%, 50% and 90% probability levels. These levels have been adopted in this work. Cumulative distribution function at



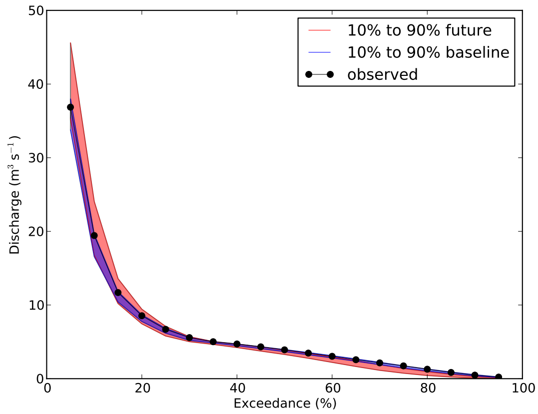
Oykel at Easter Turnaig (3003)



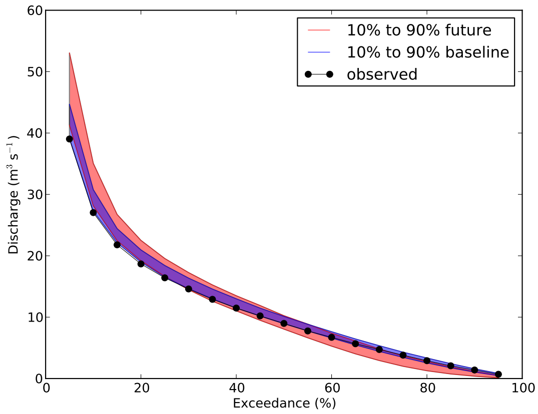
Ewe at Poolewe (94001)



Cree at Newton Stewart (81002)



Irvine at Shewalton (83005)



Deveron at Muiresk (9002)

Figure 7.16: FDCs for baseline (1961-1990) and future (2040-2069) climates compared to observed data

each exceedance probability of the FDC were created by ranking modelled flows at each of the 5th percentile intervals between Q_{95} and Q_5. This allowed predictions of flow at the 10%, 50 % and 90% levels to be extracted.

The future and baseline FDCs at 10% and 90% levels are shown in Figure 7.16 together with the FDC produced from observed gauge data. The observed data can be seen to be in agreement with the modelled baseline FDCs, tending to be closer to the upper 90% bound. This provides confidence in the ability of the model to produce plausible FDCs using the projected future weather data.

There is a clear increase in the magnitude of flows resulting from storm events at the higher FDC percentiles. There is also potential for significant decrease in baseflows. This is consistent with other findings which indicate that increased storm events will increase the magnitude of storm response and greater evapotranspiration rates will lead to reduced summer lowflows.

The modelled flow time series were used to generate average daily generation time series for the assumed scheme in each of the 5 catchments. The generation time series were used to develop simulated capacity factors for the baseline and future periods. Change factors (expressed as proportional reduction) were also calculated using the simulated capacity factors. These are detailed in Tables 7.6, 7.7, 7.8,7.9 and 7.10. Capacity factors are seen to fall on average between baseline and future periods, with significant falls in production occurring during the summer. Slightly higher capacity factors are seen in the winter, although this is limited by the choice of Q_{40} as design flow.

Although not considered further here, the results point to potential adaptation measures for run-of-river hydro in Scotland. This would largely take the form of over-sizing the turbines and potentially penstocks to take advantage of higher winter flows were. It should be noted that there is wide uncertainty associated with these results and further work is required. This could extend the approach to more catchments; incorporate the snow melt model and re-run the search algorithm under the future flow patterns to identify how the parameters of specific sites and overall capacity are impacted.

	Baseline Cap. Factor			Future Cap. Factor			Change Factor		
	10%	**50%**	**90%**	**10%**	**50%**	**90%**	**10%**	**50%**	**90%**
Jan	0.85	0.88	0.91	0.84	0.89	0.93	-0.01	0.02	0.03
Feb	0.77	0.80	0.84	0.76	0.82	0.88	-0.01	0.01	0.05
Mar	0.75	0.79	0.83	0.71	0.78	0.85	-0.05	-0.01	0.02
Apr	0.52	0.58	0.63	0.49	0.57	0.67	-0.07	-0.01	0.07
May	0.27	0.31	0.36	0.22	0.29	0.38	-0.18	-0.07	0.05
Jun	0.29	0.35	0.41	0.23	0.30	0.40	-0.22	-0.13	-0.02
Jul	0.33	0.38	0.43	0.18	0.33	0.44	-0.44	-0.13	0.03
Aug	0.44	0.48	0.53	0.24	0.37	0.51	-0.46	-0.24	-0.04
Sep	0.61	0.66	0.72	0.55	0.63	0.71	-0.09	-0.04	-0.01
Oct	0.79	0.82	0.85	0.75	0.82	0.87	-0.05	0.00	0.01
Nov	0.90	0.92	0.94	0.88	0.93	0.96	-0.02	0.01	0.02
Dec	0.86	0.89	0.91	0.85	0.92	0.97	-0.02	0.03	0.06

Table 7.6: Oykel (Q_d = 6.38, P_d = 5.3 MW)

	Baseline Cap. Factor			Future Cap. Factor			Change Factor		
	10%	**50%**	**90%**	**10%**	**50%**	**90%**	**10%**	**50%**	**90%**
Jan	0.80	0.85	0.89	0.84	0.90	0.94	0.04	0.05	0.06
Feb	0.73	0.79	0.84	0.77	0.84	0.90	0.06	0.06	0.07
Mar	0.70	0.76	0.81	0.74	0.81	0.87	0.05	0.07	0.08
Apr	0.52	0.57	0.62	0.49	0.60	0.70	-0.05	0.05	0.13
May	0.31	0.38	0.44	0.29	0.37	0.48	-0.06	0.00	0.09
Jun	0.30	0.36	0.41	0.26	0.33	0.43	-0.14	-0.06	0.05
Jul	0.34	0.39	0.45	0.23	0.33	0.45	-0.33	-0.17	-0.01
Aug	0.41	0.47	0.52	0.27	0.38	0.47	-0.34	-0.19	-0.11
Sep	0.62	0.66	0.73	0.59	0.66	0.74	-0.04	0.00	0.02
Oct	0.77	0.83	0.87	0.75	0.85	0.92	-0.03	0.02	0.06
Nov	0.83	0.87	0.91	0.85	0.91	0.96	0.02	0.05	0.06
Dec	0.83	0.87	0.90	0.84	0.93	0.96	0.01	0.07	0.07

Table 7.7: Ewe (Q_d = 19.45, P_d = 16.3 MW)

	Baseline Cap. Factor			Future Cap. Factor			Change Factor		
	10%	**50%**	**90%**	**10%**	**50%**	**90%**	**10%**	**50%**	**90%**
Jan	0.83	0.87	0.89	0.83	0.88	0.94	-0.01	0.02	0.05
Feb	0.76	0.80	0.83	0.77	0.83	0.88	0.01	0.04	0.06
Mar	0.71	0.75	0.78	0.67	0.75	0.82	-0.05	0.00	0.04
Apr	0.50	0.55	0.60	0.44	0.53	0.63	-0.12	-0.04	0.05
May	0.33	0.37	0.42	0.27	0.34	0.43	-0.18	-0.07	0.02
Jun	0.31	0.36	0.42	0.15	0.27	0.39	-0.51	-0.24	-0.05
Jul	0.37	0.43	0.47	0.20	0.32	0.43	-0.45	-0.25	-0.10
Aug	0.51	0.56	0.62	0.23	0.38	0.55	-0.56	-0.32	-0.11
Sep	0.67	0.71	0.76	0.57	0.64	0.72	-0.15	-0.10	-0.05
Oct	0.80	0.83	0.86	0.76	0.81	0.88	-0.06	-0.02	0.03
Nov	0.88	0.90	0.92	0.88	0.92	0.96	0.01	0.03	0.05
Dec	0.84	0.87	0.90	0.84	0.89	0.94	0.00	0.02	0.04

Table 7.8: Cree (Q_d = 10.07, P_d = 8.4 MW)

	Baseline Cap. Factor			Future Cap. Factor			Change Factor		
	10%	**50%**	**90%**	**10%**	**50%**	**90%**	**10%**	**50%**	**90%**
Jan	0.92	0.94	0.95	0.92	0.95	0.98	0.01	0.01	0.02
Feb	0.88	0.91	0.93	0.85	0.90	0.94	-0.03	-0.01	0.01
Mar	0.77	0.80	0.84	0.72	0.79	0.85	-0.06	-0.02	0.01
Apr	0.52	0.59	0.66	0.45	0.57	0.65	-0.14	-0.03	-0.01
May	0.26	0.31	0.36	0.19	0.26	0.38	-0.26	-0.15	0.06
Jun	0.20	0.25	0.30	0.08	0.14	0.25	-0.61	-0.43	-0.16
Jul	0.27	0.33	0.39	0.13	0.22	0.35	-0.53	-0.34	-0.13
Aug	0.43	0.49	0.55	0.15	0.29	0.44	-0.66	-0.41	-0.21
Sep	0.72	0.76	0.80	0.56	0.67	0.77	-0.22	-0.11	-0.04
Oct	0.87	0.90	0.93	0.81	0.87	0.92	-0.07	-0.04	-0.01
Nov	0.94	0.96	0.97	0.92	0.96	0.98	-0.02	0.00	0.01
Dec	0.90	0.92	0.94	0.90	0.94	0.96	0.00	0.02	0.02

Table 7.9: Irvine (Q_d = 4.21, P_d = 3.5 MW)

	Baseline Cap. Factor			Future Cap. Factor			Change Factor		
	10%	**50%**	**90%**	**10%**	**50%**	**90%**	**10%**	**50%**	**90%**
Jan	0.92	0.95	0.97	0.92	0.96	0.98	0.00	0.01	0.01
Feb	0.88	0.91	0.94	0.89	0.93	0.97	0.01	0.02	0.03
Mar	0.79	0.84	0.87	0.77	0.85	0.90	-0.04	0.01	0.03
Apr	0.60	0.66	0.70	0.52	0.63	0.73	-0.13	-0.04	0.03
May	0.38	0.44	0.50	0.30	0.41	0.49	-0.23	-0.07	-0.02
Jun	0.25	0.30	0.36	0.16	0.23	0.32	-0.37	-0.23	-0.13
Jul	0.22	0.28	0.34	0.10	0.18	0.31	-0.55	-0.34	-0.08
Aug	0.30	0.39	0.44	0.14	0.25	0.38	-0.53	-0.35	-0.13
Sep	0.46	0.54	0.60	0.32	0.43	0.55	-0.31	-0.20	-0.09
Oct	0.69	0.75	0.81	0.62	0.73	0.82	-0.11	-0.04	0.01
Nov	0.87	0.91	0.94	0.87	0.92	0.97	0.00	0.01	0.02
Dec	0.94	0.96	0.98	0.94	0.97	0.99	0.00	0.01	0.01

Table 7.10: Deveron (Q_d = 10.8, P_d = 9 MW)

7.8 Discussion of Discount Rates

The range of results produced by the ROR search for the different discount rates corresponds well with the estimates produced from other studies. This indicates that the schemes identified in terms of use of raw resource by those studies are valid, however different assumptions relating to cost, revenue and external costs such as grid connection and reinforcement will have a large impact upon the final result. The discount rate has been used in this work to represent the cost of finance and risk associated with hydropower projects. Project risk can come from capital costs exceeding those budgeted, variance in energy yield due to climatic variability, variance in electricity price due to changes in market fundamentals or structure. While the subsidies received by a single hydropower scheme would be expected to be fixed over the lifetime of the project, development of multiple projects over a period of time could result in different projects experiencing different levels of support due to changes in policy. Use of a range of discount rates is necessary to capture the future uncertainty associated with development of renewable energy schemes.

In an attempt to give some meaning to the risk represented by the different discount rates and subsequent identified capacity, an assessment is made here of potential external and unquantifiable factors that will impact development of hydro resource. This is an unashamedly qualitative exercise.

5% discount rate; classified as ‘low risk’ (unlocking 898 MW):

- Positive public opinion
- Strong government support
- Supportive planning regime, hydropower development a priority
- Subsidy increased to reflect predictability and high capacity factor
- Stable subsidy regime, fixed over long term with clear terms
- Low cost finance available from institutions such as the proposed Green Investment Bank
- Shallow / socialised grid connection costs
- Improved cost estimation and surveying methods
- Robust resource assessment methods.

10% discount rate; classified as ‘medium risk’ (unlocking 440 MW):

- Mixed public opinion, with majority in favour
- Broad government support
- Receptive planning / licensing regime but certain schemes not permitted in certain sensitive areas
- Subsidy regime re-designed every 5 to 10 years
- Parity with funding available to other renewable generation types
- Connection costs met by developer, however upstream reinforcement costs limited

15% discount rate; classified as ‘high risk’ (unlocking 203 MW):

- Poor public opinion
- Limited government support
- Hostile planning regime but schemes rejected in many locations
- Project finance limited to expensive sources
- Significant cost overruns, poor contractor performance, material shortages / price fluctuations, labour disputes
- Significant volatility in electricity prices
- Subsidy regime threatened
- All connection costs including all required upstream reinforcement to be met by developer

7.9 Chapter Summary

This chapter presents the schemes identified as by the ROR and impoundment searches at a range of discount factors. The aggregate total of identified sites was found to vary significantly with discount rate. Comparison was made with other studies and while agreement was found for mid-sized schemes, a larger number of sub 1 MW sites were identified in the NFA (2008) study. It is believed that this is due to differences in cost assumptions and the inclusion of 11 kV connections to assumed points of connection within the NFA methodology. The spatial distribution of schemes is presented and the large influence of proximity to transmission lines presented.

A hindcast of hydropower production from the identified ROR sites for the 10% discount rate scenario has been performed showing the variance in total production between days, months and years. The aggregate time series showing that run-of-river hydro is capable of providing sustained power delivery over the winter albeit with much poorer performance during the summer.

A preliminary assessment of how a changing climate may affect generation has been made for hypothetical schemes modelled within 5 catchments using future and baseline data from the UKCP09 weather generator. This shows that increased flows may allow increased generation during the winter, however summer flows are greatly reduced impacting summer generation. The current seasonal pattern of generation is likely to become more pronounced in the future.

8
Summary and Discussion

"Prediction is very difficult, especially about the future."

– Niels Bohr

8.1 Introduction

The goal of this work has been to develop a robust survey of the temporal and spatial distribution of Scotland's unexploited hydropower resource. To achieve this geophysical tools have been combined with a distributed hydrological model and technical and financial hydropower project models. An assessment of run-of-river and impoundment sites has been undertaken. An investigation of the effect a changing climate will have on the resource was also made.

8.2 Work Undertaken

Chapter 1 provides an introduction to the work, giving context and background and stating aims and objectives.

Chapter 2 presents a literature survey undertaken to identify the state-of-the-art in hydropower resource assessment and the key techniques required to undertake such an investigation.

Chapter 3 details the development of long-term gridded time-series datasets for rainfall, evapotranspiration and temperature and provides assessment of the error and validation against available measured data. These datasets enable a distributed hydrological model to be used to simulate river flows Scotland-wide for the period 1961 to 2005 at daily temporal resolution.

Chapter 4 describes the development of datasets representing the spatial characteristics of Scottish rivers. Several datasets varying in spatial resolution were produced to enable flow routing within a distributed hydrological model to be performed. An addressed river network was developed allowing database search methods to be used to enable a hydropower search method.

Chapter 5 details the development of an implementation of the G2G hydrological model used to simulate daily flow time series. The model was validated and calibrated at 1 km resolution. A simple regionalisation was performed based upon the average performance for a given set of parameters of gauged catchment models within each of the 3 SEPA regions. Once parameterised, the model was run at 200 m resolution for the period 1961 to 2005. To validate the model the long term simulated time-series were compared to available gauge values.

Chapter 6 describes a method developed to make use of the distributed flow time series and river network data to allow searches for potential economically viable run-of-river and impoundment sites to be performed.

Chapter 7 presents the results of the hydropower search method and compares these to the findings of other studies. In addition, it demonstrates how credible time series of production can be simulated for the newly identified sites. To investigate how climate change will affect Scotland's hydropower resource a number of catchments were modelled using baseline and future data produced using the UKCP09 Weather Generator. Hypothetical hydropower plant were placed in each of these catchments and time series power production under baseline and future climate were simulated allowing the change in capacity factor to be assessed at different probability levels.

8.3 Discussion

Development of a robust approach to estimate Scotland's remaining hydropower potential has required use a number of datasets and methods. At each stage significant attention has been paid to minimising the contribution to overall uncertainty and error in the final results.

A comprehensive dataset of UKMO rain gauge data was used to develop gridded rainfall datasets, the number spatial distribution and data integrity of which was found to vary over time. There is also a lack of rain gauges located in upland areas especially at the highest elevations suggesting that precipitation levels will tend to be underestimated. A rainfall climatology (SAAR dataset) was used to weight a generated interpolation surface, improving the representation of gridded rainfall in upland areas. A simple method was used to downscale gridded temperature data; while the results appear realistic it was difficult to validate the method as there are few high elevation met stations. A monthly evapotranspiration dataset was constructed and validated. Ideally a daily dataset would have been created, however this would have significantly increased data requirements. A grass surface was assumed, simplifying application of the FAO-56 method, at the expense of making the resulting PET surfaces more uniform.

An implementation of the G2G model was used with the generated gridded data to develop robust long term simulated flow time-series across the Scottish river network. Difficulty was encountered closing the water balance, with simulated flow volumes not equalling those measured at gauges over longer time frames, however this is an almost universal problem experienced in hydrological practice. The G2G model structure was found to underestimate low flows especially during summer recession periods with moisture stores being emptied. Parameter uncertainty was investigated through use of the GLUE method, with a range of parameter values found to produce similar levels of performance from the model. A simple but robust regionalisation was performed by identifying a common best fit for catchments within the three SEPA regions, developing relationships between parameters and catchment descriptors could potentially improve the parameterisation of ungauged catchments. Assessment of the error in model predictions at ungauged locations is difficult to achieve, however it was found that the error in volume between simulated and observed long term time series represented as flow duration curves was typically between 10 and 20%, it is reasonable to assume that this is the level of error introduced to energy yield predictions.

A simple degree day model was used to account for the contribution of snow held in upland catchments to the winter/spring hydrological regime. Given the scale of this work it was difficult to assess the impact of snowmelt to spring runoff in detail, although a reduction in average runoff during February and increase in March was observed. Focus on a single upland catchment with a large quantity of winter snow pack together with snow depth data and perhaps visual assessment of the snowline would allow a more thorough assessment to be made.

The OS Profile DEM used to provide elevation values for calculating head is limited in accuracy to ± 0.5 m introducing uncertainty to the feasibility of identified low head sites. In addition it was found that erroneous values were included in the DEM especially in built up areas or at the bottom of sharp edges introduced by embankments or at the bottom of narrow gorges.

A major objective of the work was to create a repeatable methodology that would allow multiple searches using different parameter values. While this was almost entirely achieved, it was necessary to manually remove certain identified sites that conflicted with existing hydropower schemes. The identified affected river reaches could be marked for exclusion in further searches enabling a fully automated repeatable procedure.

It has been assumed in this work that all identified sites will be able to connect to the 33 kV distribution network without consideration of the costs of reinforcement. In reality the availability of connection will depend upon the characteristics of the local network, with nearby generators and loads taken into consideration. The only method of assessing this is to perform load flow analysis of the network to determine the impact a planned scheme will have on the thermal rating, fault level and system voltages.

Planning conditions and limitation of development in sensitive areas has not been considered. While the impact of these factors will be determined based upon political considerations it is unlikely that all identified sites will be able to obtain planning consent, or approval of landowners and the public.

A very simple approach was used to consider varying market prices and the strategy that could be used by impoundment sites to maximise revenue. Using operating rules of greater sophistication would enable a more realistic and potentially more beneficial treatment of impoundment operation to be made in terms of financial scheme performance.

Identification of viable hydropower schemes was considered based upon economic merit this made the use of cost models necessary. The best available public domain cost model RETScreen was utilised however this is based upon data from North American projects, and is older than would have been ideal.

8.4 Final Conclusions

The method presented in this work has allowed a robust assessment of Scotland's run-of-river hydropower potential to be made. In addition, a method for identification of impoundment sites has been demonstrated. At a 10% discount rate, 440 MW of run-of-river hydropower was identified contributing 1750 GWh on average or roughly 4% of the Scottish Government's 100% renewable electricity target. This is a not inconsiderable potential contribution with much scope for enhancement. The discount rate was found to have a large impact on the number and size of identified sites with the 5% and 15% scenarios producing a range of potential between 204 MW and 898 MW. The final results are summarised in table 8.1.

Discount Rate	**No. of Sites**	**Total Capacity (MW)**	**Energy Delivery (GWh)**	**Contribution to 100% target**
5%	694	898	3164	8%
10%	339	440	1749	4%
15%	146	204	869	2%

Table 8.1: Number of identified economic hydropower sites, total capacity, average annual energy delivery and contribution to Scottish Government 100% renewable electricity target at 5%, 10% and 15% discount rates

Development of long-term daily average flow time series using a distributed hydrological model allows temporal analysis of production. A long-term hindcast of aggregate production was created for the 440 MW of run-o-river schemes identified under the 10% discount rate scenario for the period 1962-2004. Average monthly energy production and capacity factors were calculated using the hindcast generation data. This analysis shows strong seasonal production variability with aggregate capacity factor ranging from 57% in December to below 20% in June. It was found that there are significant periods during winter when nearly full production is sustained over consecutive days.

An initial investigation of the impact of climate change has shown that seasonal variability of the resource is likely to become more pronounced. Capacity factors were shown to have a high probability of increasing during winter while falling during summer. If new schemes are designed based upon the existing climate without consideration for these changes then they may experience sub-optimal performance. If design flow is increased in anticipation of higher winter flows then annual yield could potentially be increased. This also suggests that existing schemes could potentially be repowered with higher capacity turbines or increased impoundment volume, for example by increasing dam heights, to take advantage of increased winter flows and reduce overspills. Given the importance of hydropower in Scotland's energy mix, further investigation into the effects of climate change on the resource is crucial.

Development of Scotland's renewable potential will depend upon the availability of access to the grid, development of which is focussed upon upgrade of HV transmission infrastructure. As renewables, especially hydro are dispersed small generators, use of distribution infrastructure is likely to increase. It was found that scheme distance from the existing electricity network had a large impact on viability, due to the costs of constructing lengthy transmission lines. While this is by no means a new issue it is worthwhile labouring the point that new hydropower development will largely be determined by the cost of connecting to the grid.

8.5 Further Work

To further investigate the change to hydropower resource under a future climate the G2G model could be used with RCM output such as the UKCP09 11 run ensemble to produce flow time-series. The hydro search could then be rerun with these future flows and the resulting schemes compared with those identified under the present climate.

Increased use of variable renewables such as wind power increases the need for suitable methods of energy storage. Currently the only viable, proven, technology is pumped storage. This work has developed methods that may be used to assess the feasibility of pumped storage. The dam search algorithm could be used to identify suitable impoundments at high elevation situated near to large waterbodies.

Further investigation into identified impoundment schemes could be performed. The use of tunnels and aqueducts to increase catchment area, as featured in many existing schemes, could potentially increase the size of identified sites. The use of tunnels instead of penstocks could also highlight alternative schemes. More sophisticated localised optimisation could be developed with more complex layouts and the ability investigate the development of cascaded schemes. Use of OS Mastermap data would allow a more accurate assessment of location of weirs and river features.

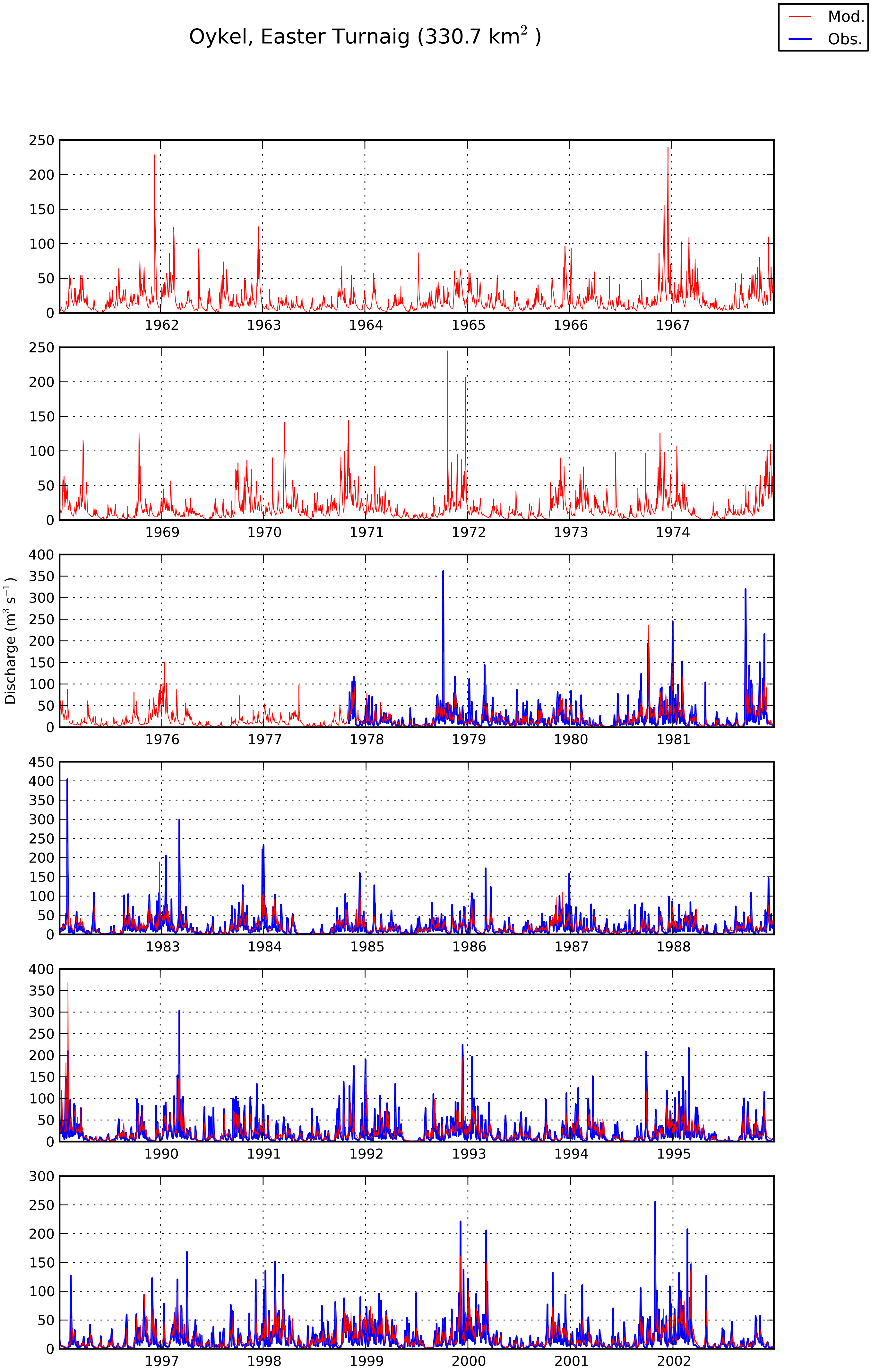
Assessment of clustering schemes would allow a more economic approach to connection to be considered. Development of a network model to enable load flow to be performed in an integrated way allowing assessment of likely network impacts and requirement for reinforcement. Creation of maps of the 11 kV network would enable connection at this voltage to be assessed.

The operation of renewable generators is treated as commercially sensitive by operators with reluctance to share production and cost data. Availability of this data together with ‘at site’ resource measurements made by operators, would significantly aid the process of developing a resource model and would allow further validation to be made. This would ultimately allow policy to be formed from a much better understanding of resource characteristics. Given that renewable generators receive public financial support it is surprising that greater transparency is not required by the regulator Ofgem.

Investigation into the benefit of increasing impoundment size and reservoir volume of existing Scottish hydropower schemes operating within a future climate is recommended. Increased storage volume would reduce overspills and could potentially allow annual average production to be maintained despite reduced summer operation.

This work has demonstrated the application of a whole of Scotland hydrological model to allow long term estimates of flow to be made in ungauged catchments. While the focus of this work was to develop understanding of the remaining Scottish hydropower resource, the models and methods have wider applicability. There is clear potential for use in areas of the world where hydropower remains undeveloped and which also lack sufficient river gauge data to enable robust resource assessment.

Appendix A
Long term Simulated Hydrographs


Oykel, Easter Turnaig (330.7 km^2)
Mod.
Obs.
Discharge (m^3 s^{-1})
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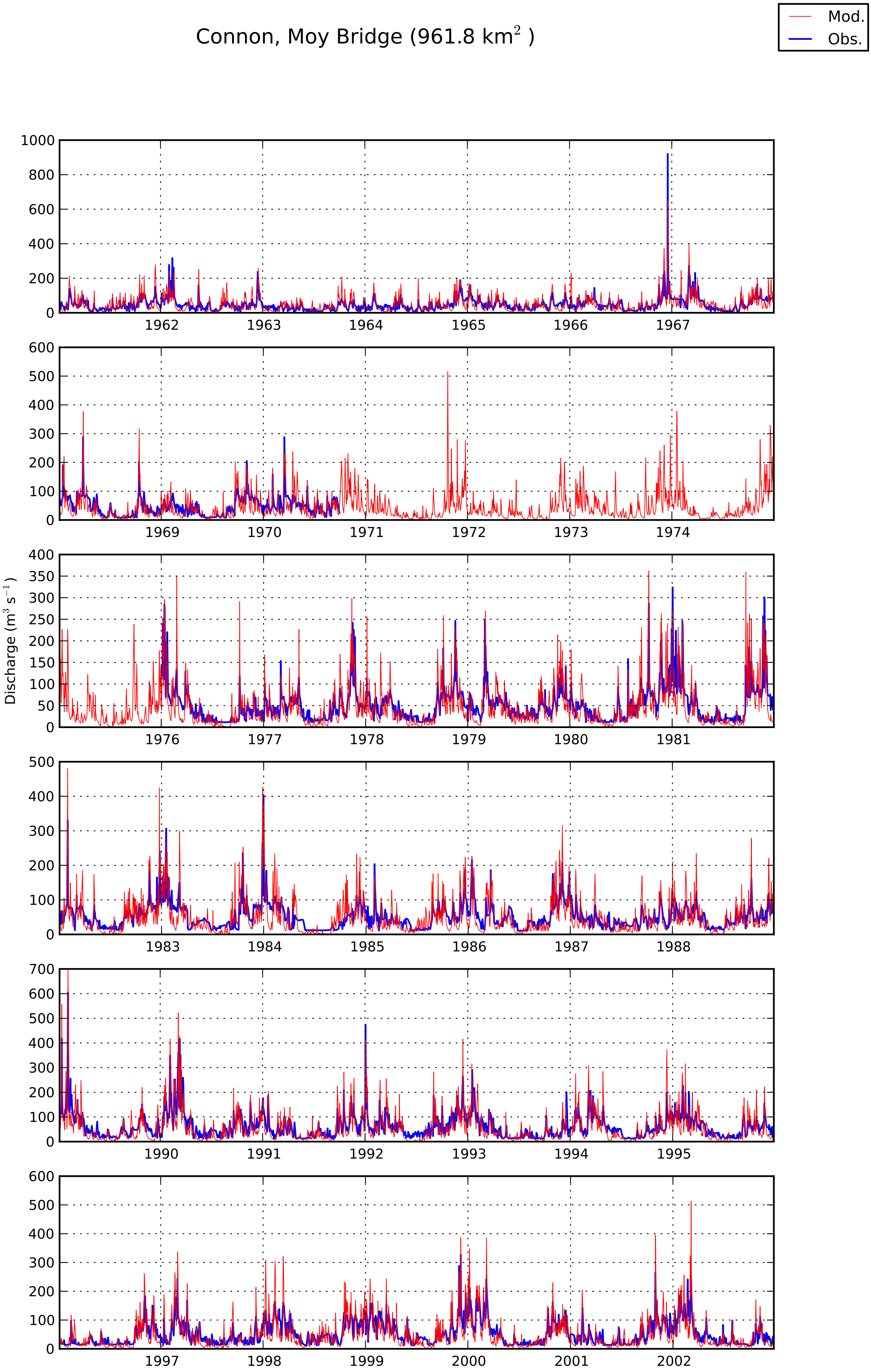
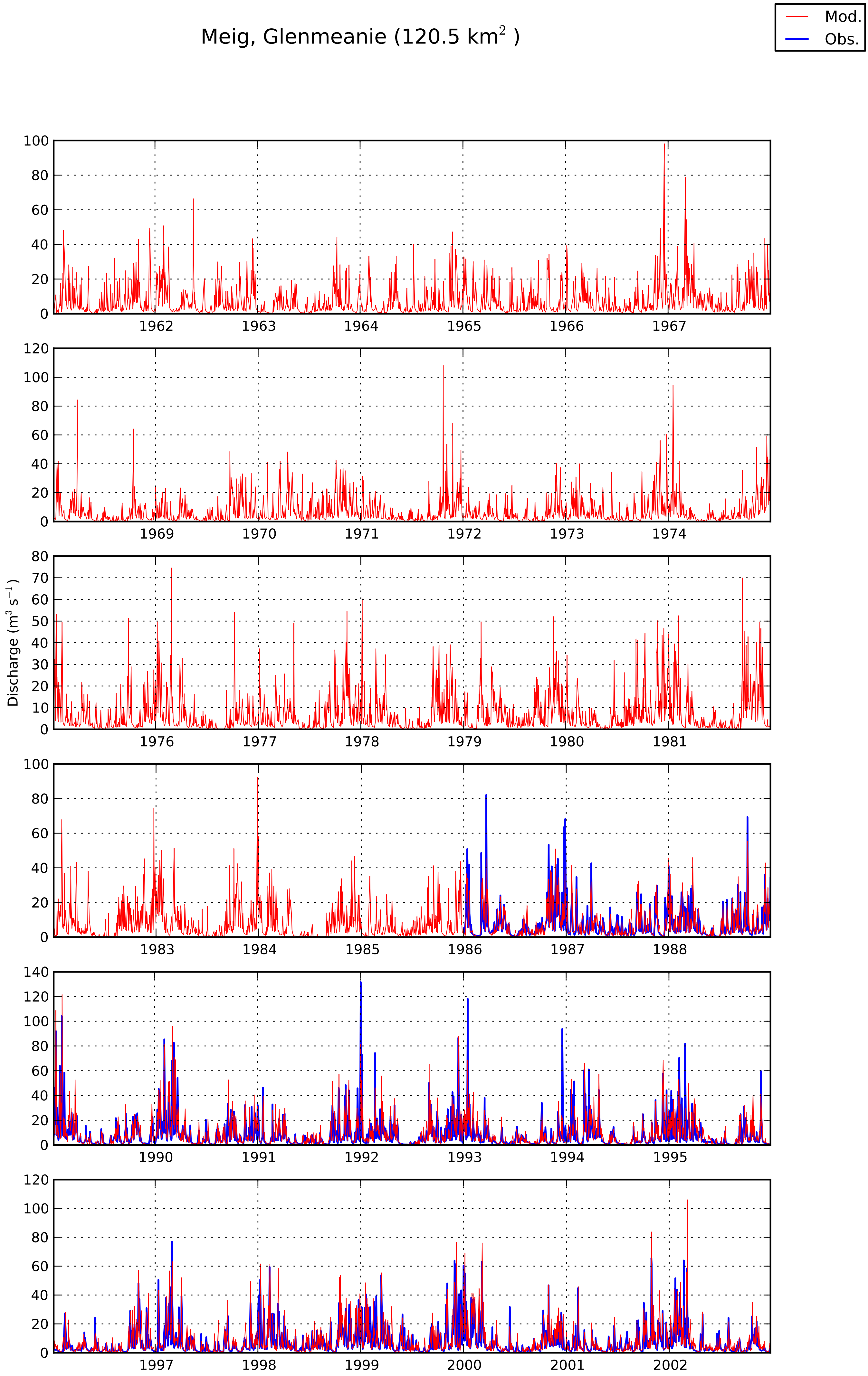
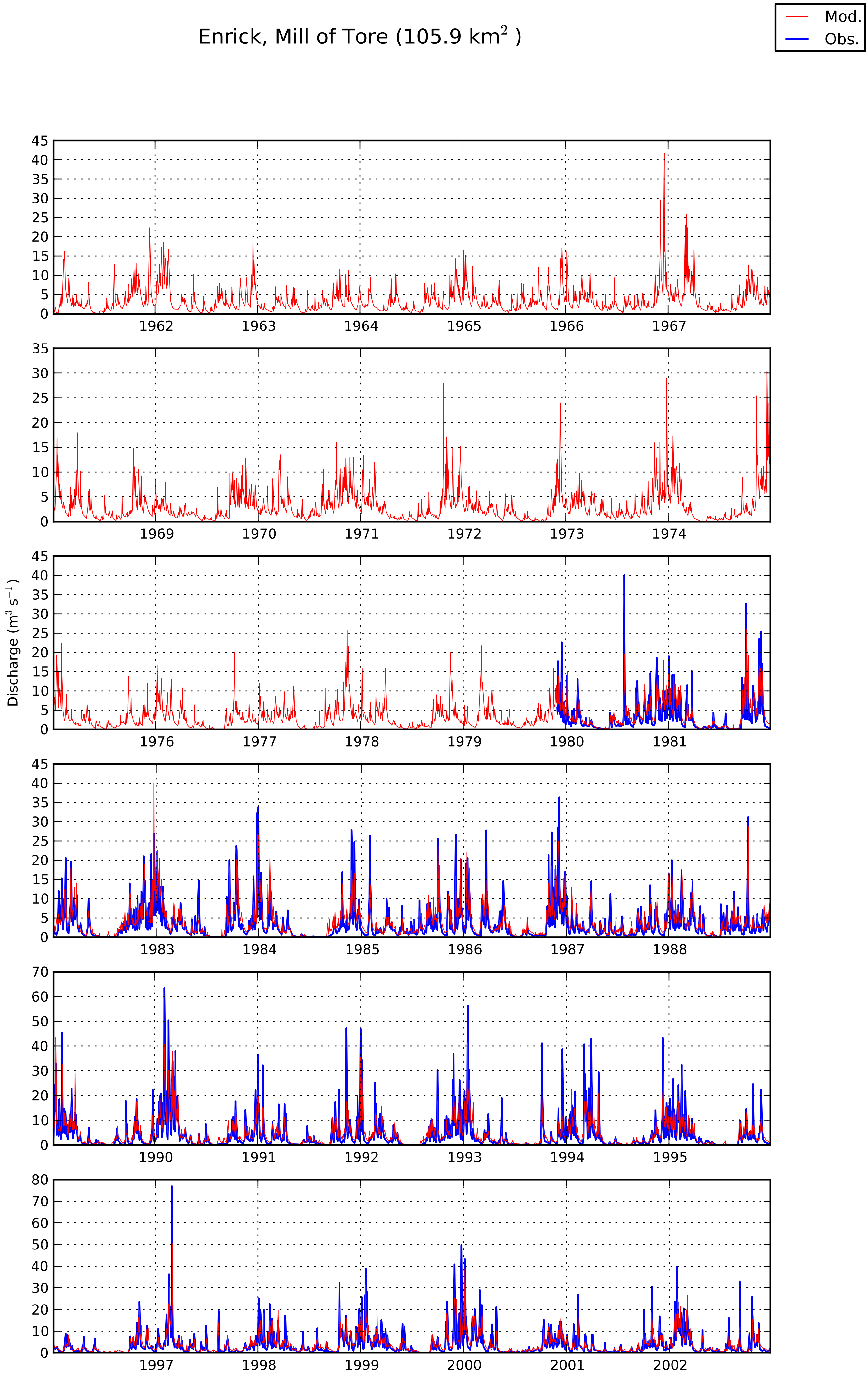

Connon, Moy Bridge (961.8 km^2)
Mod.
Obs.
Discharge (m^3 s^{-1})

Meig, Glenmeanie (120.5 km^2)




Enrick, Mill of Tore (105.9 km^2)
Mod.
Obs.
Discharge (m^3 s^{-1})
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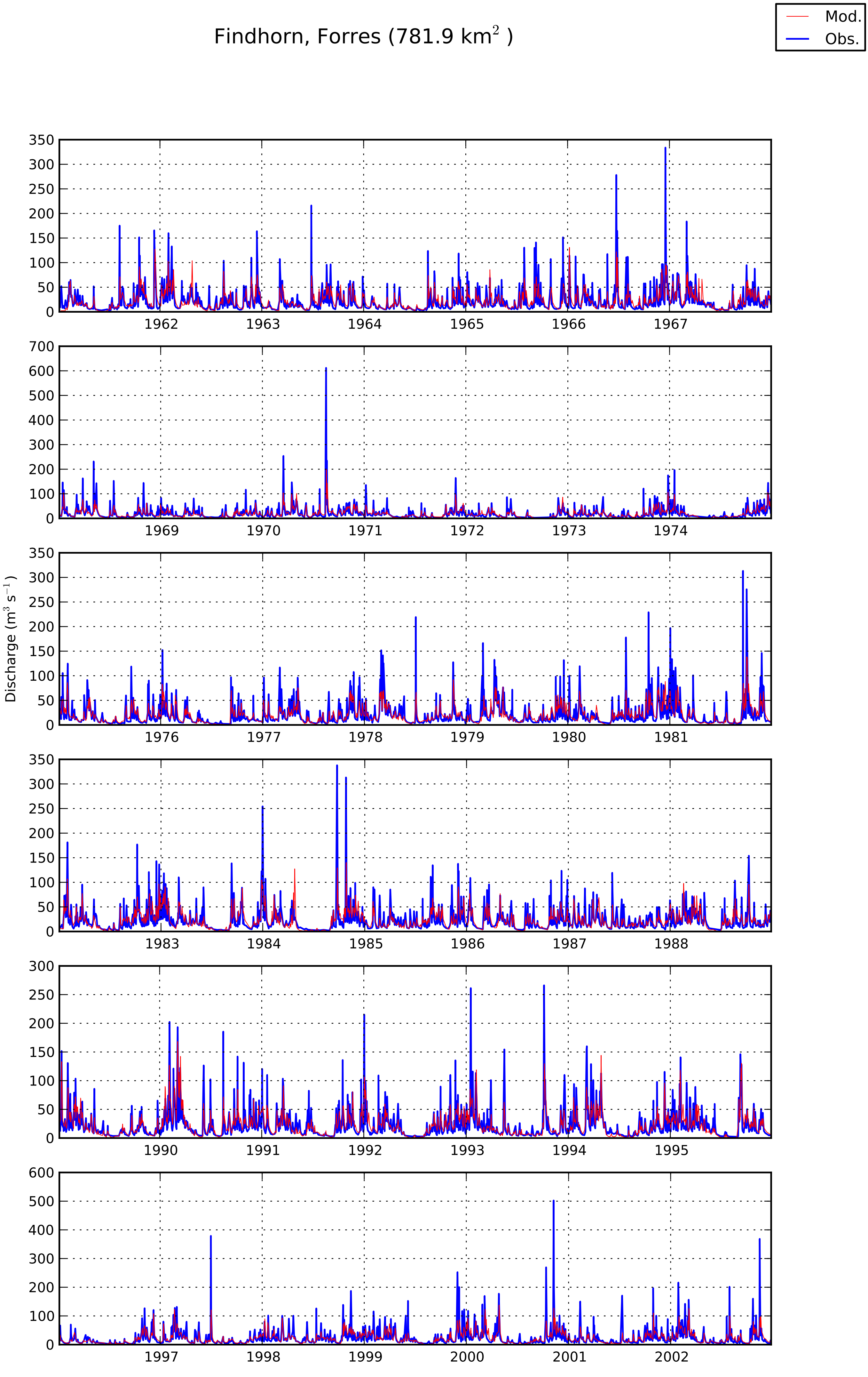
Findhorn, Forres (781.9 km^2)
Mod.
Obs.
Discharge (m^3 s^{-1})
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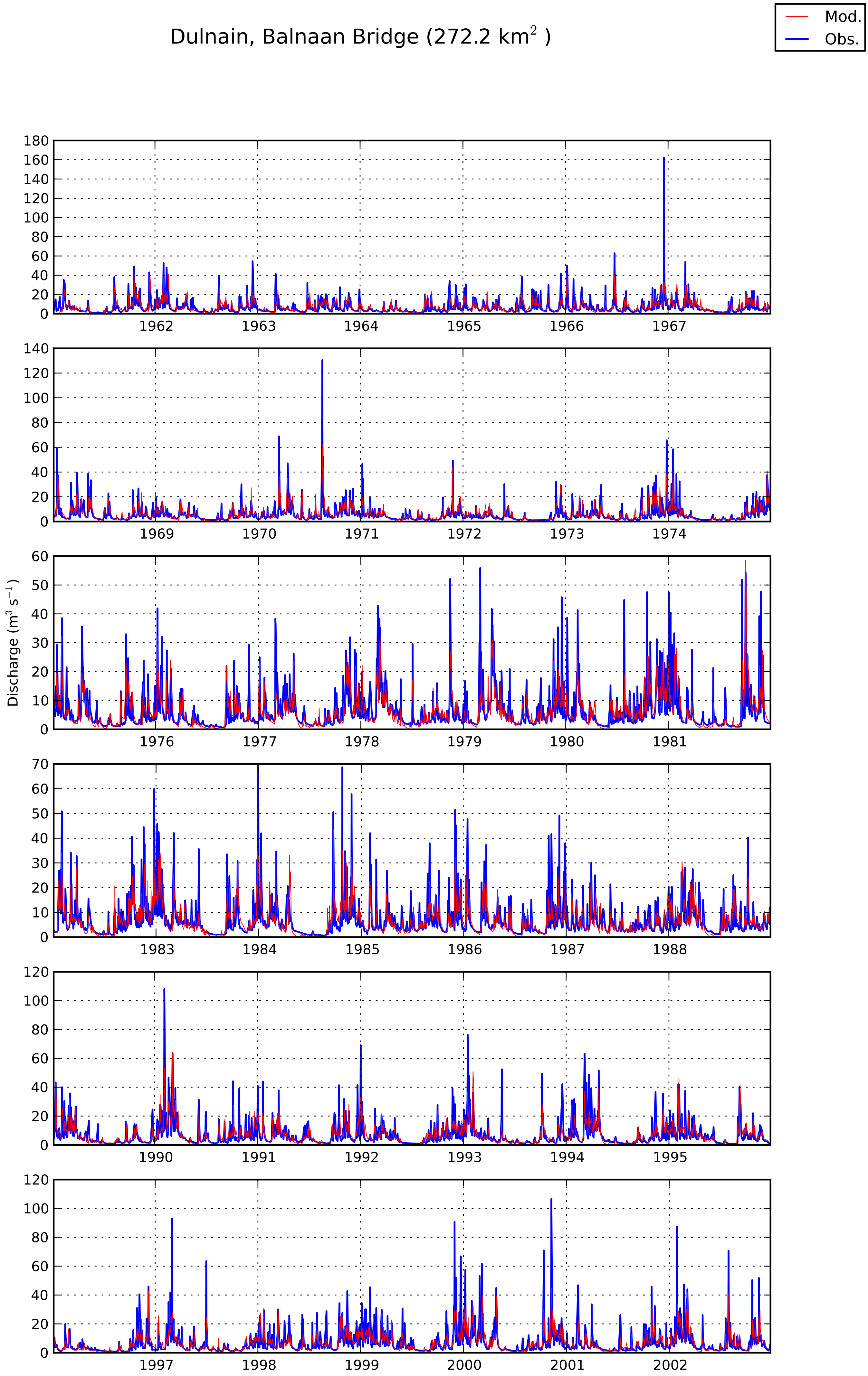
Dulnain, Balnaan Bridge (272.2 km^2)
Mod.
Obs.
Discharge (m^3 s^{-1})
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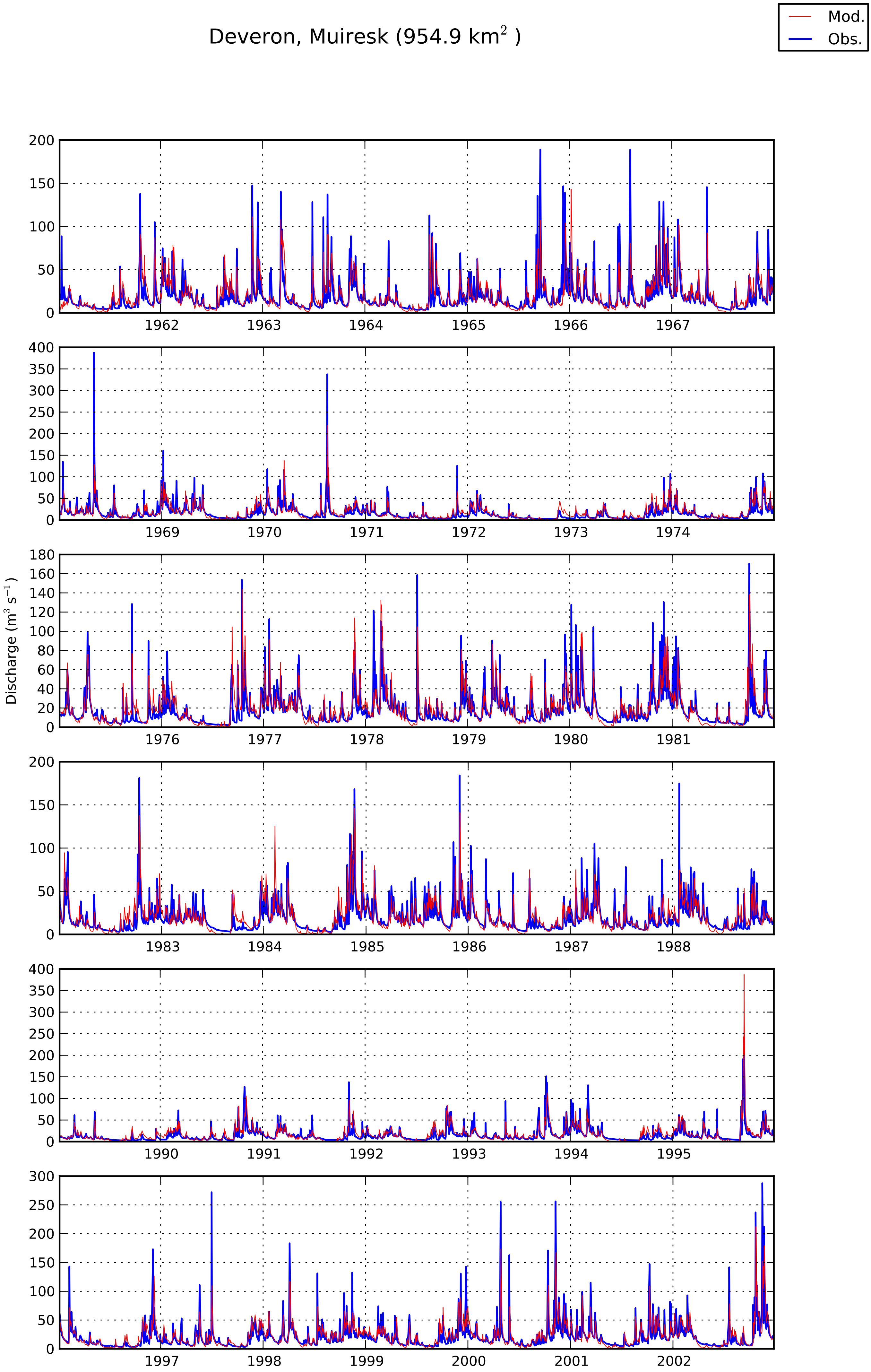

Deveron, Muiresk (954.9 km^2)
Mod.
Obs.
Discharge (m^3 s^{-1})
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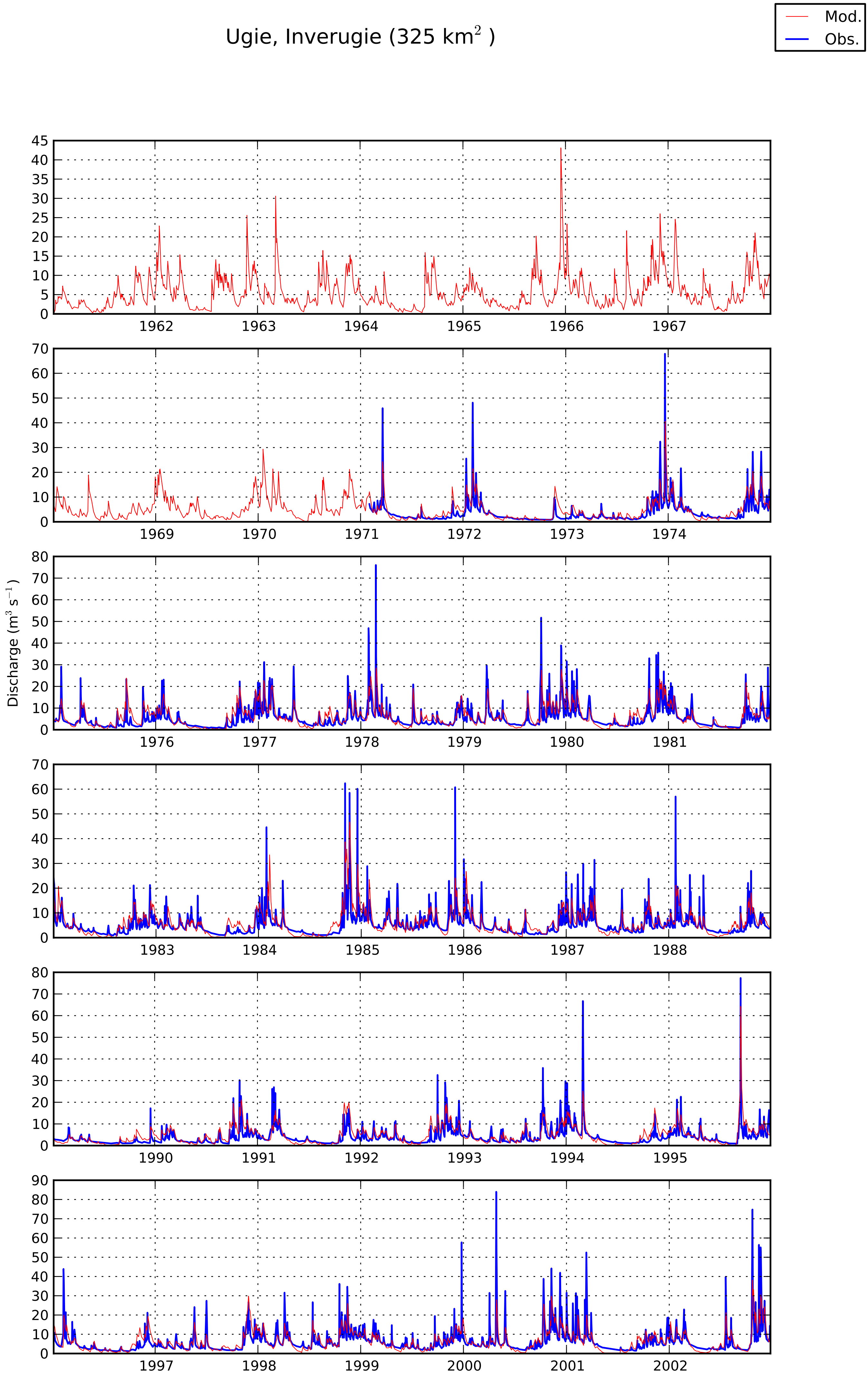
Ugie, Inverugie (325 km^2)
Mod.
Obs.
Discharge (m^3 s^{-1})
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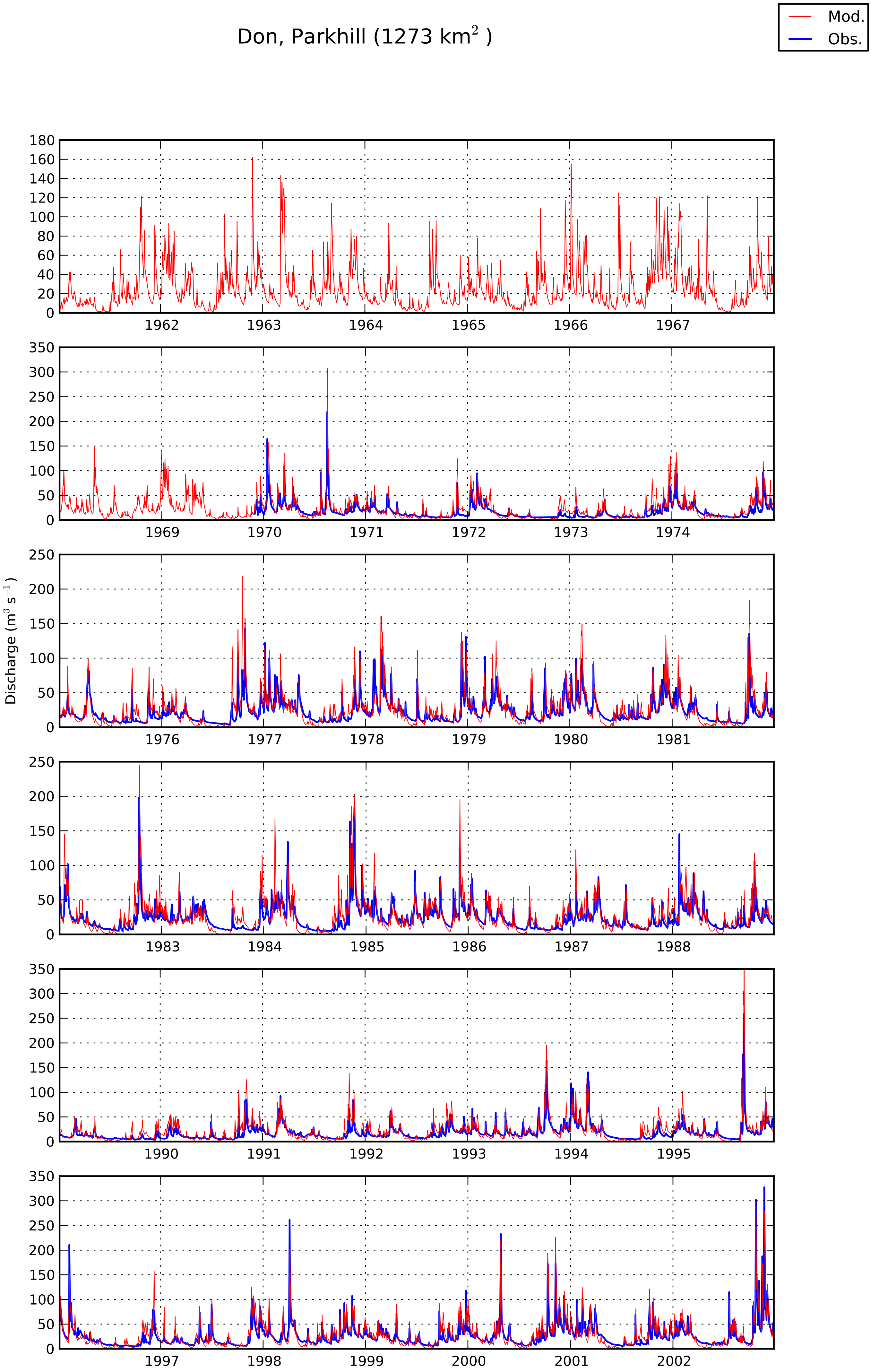
Don, Parkhill (1273 km^2)
Mod.
Obs.
Discharge (m^3 s^{-1})
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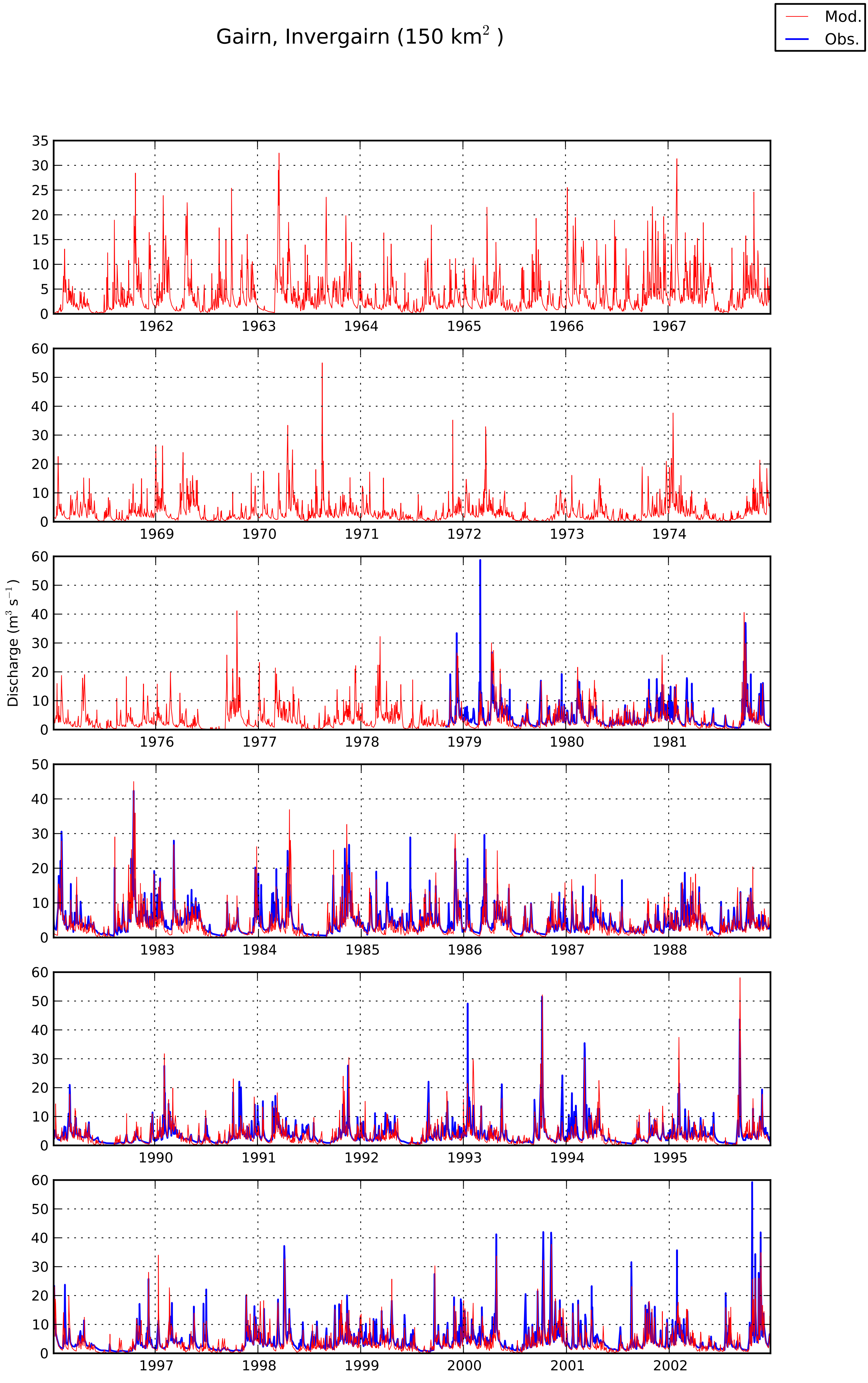
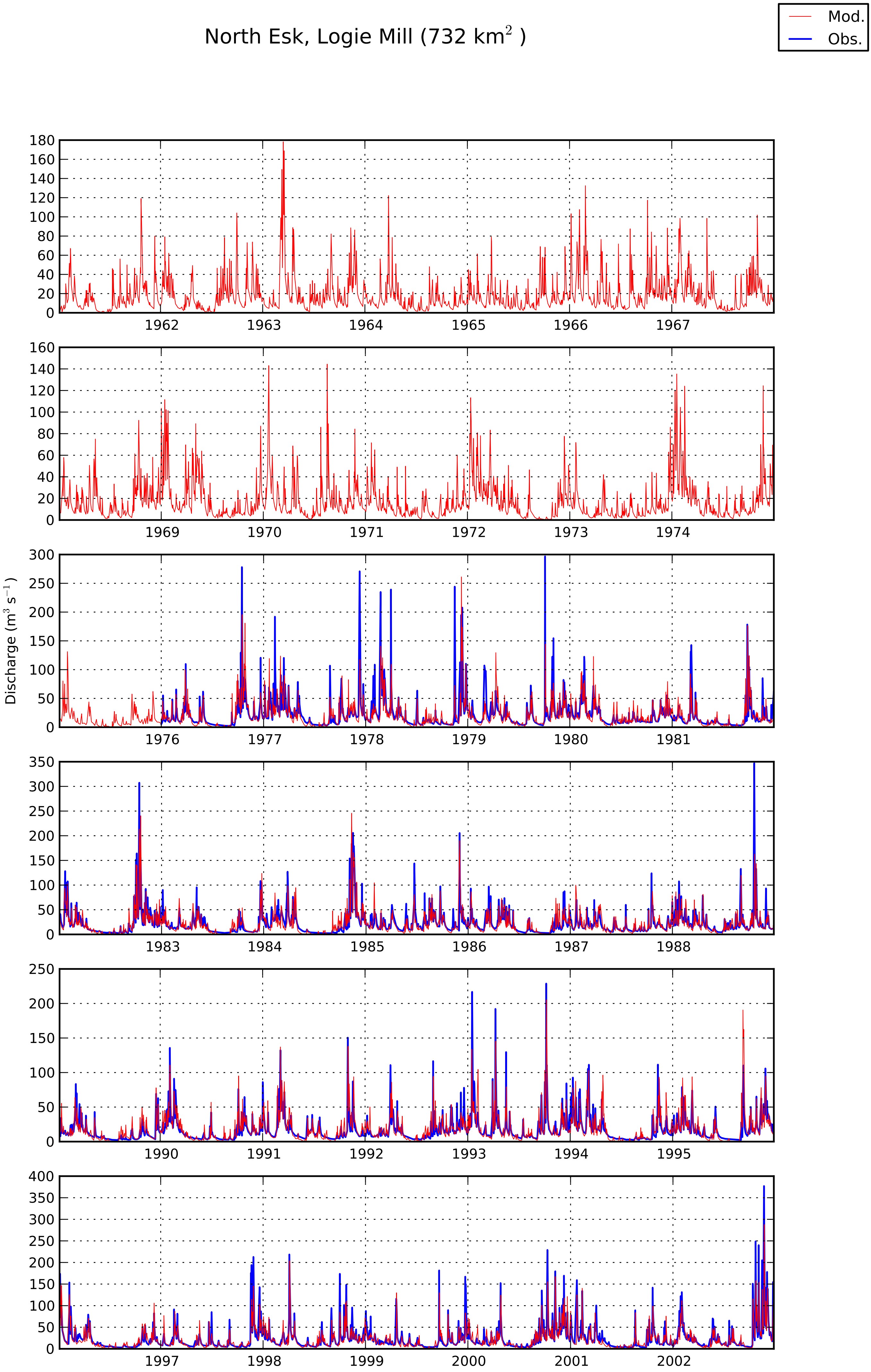
Gairn, Invergairn (150 km^2)




North Esk, Logie Mill (732 km^2)
Mod.
Obs.
Discharge (m^3 s^{-1})
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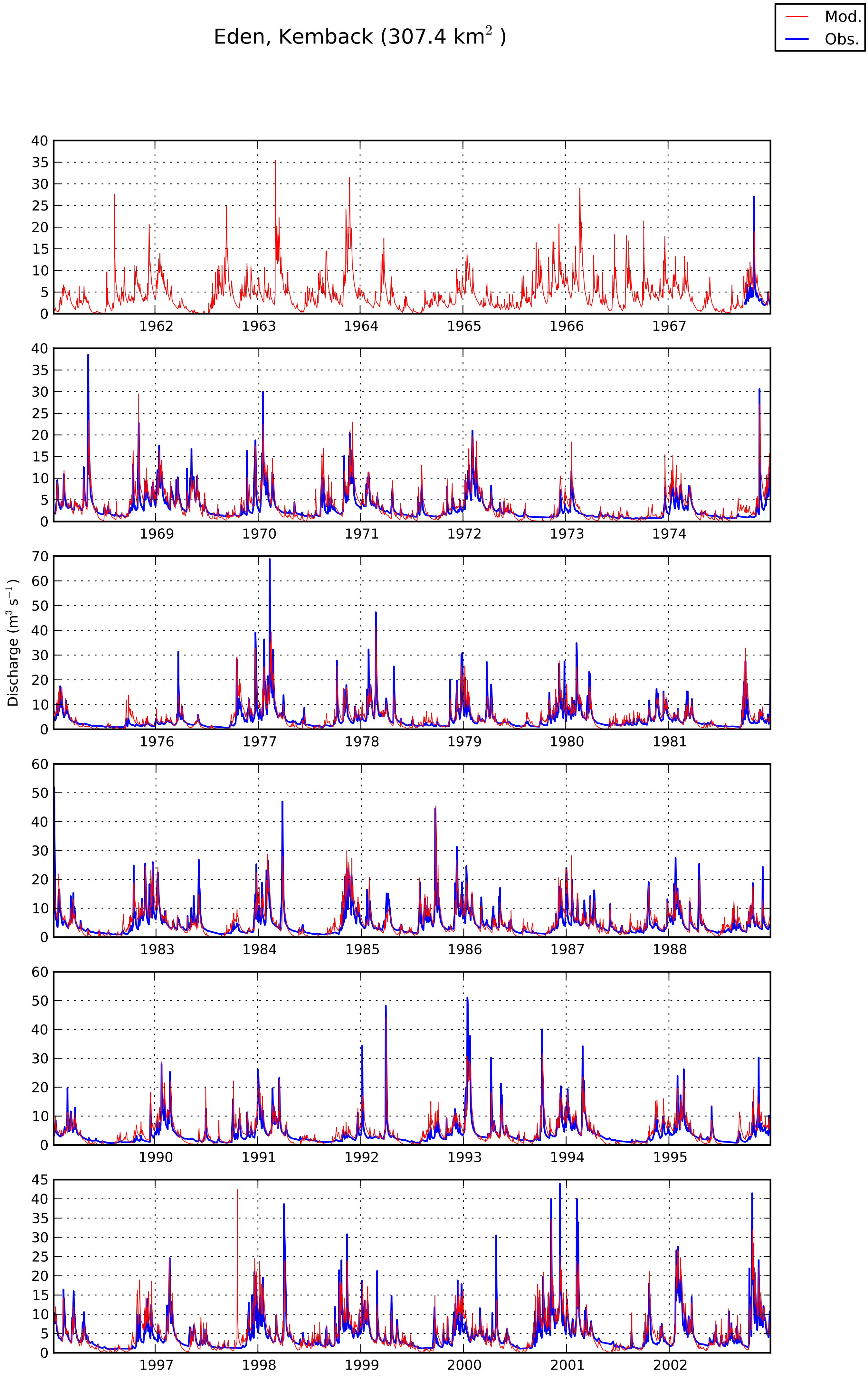

Eden, Kemback (307.4 km^2)
Mod.
Obs.
Discharge (m^3 s^{-1})
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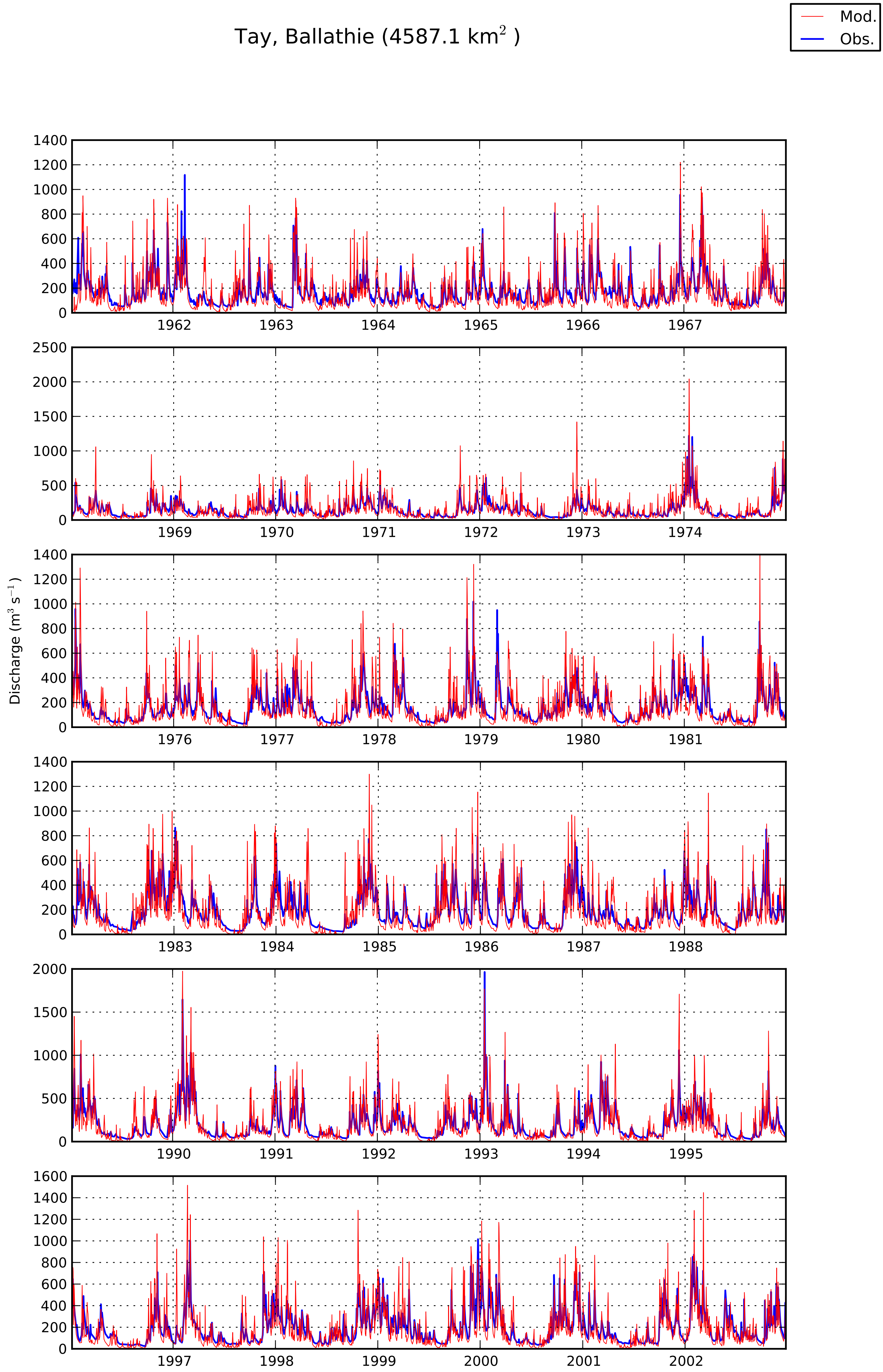
Tay, Ballathie (4587.1 km^2)
Mod.
Obs.
Discharge (m^3 s^{-1})
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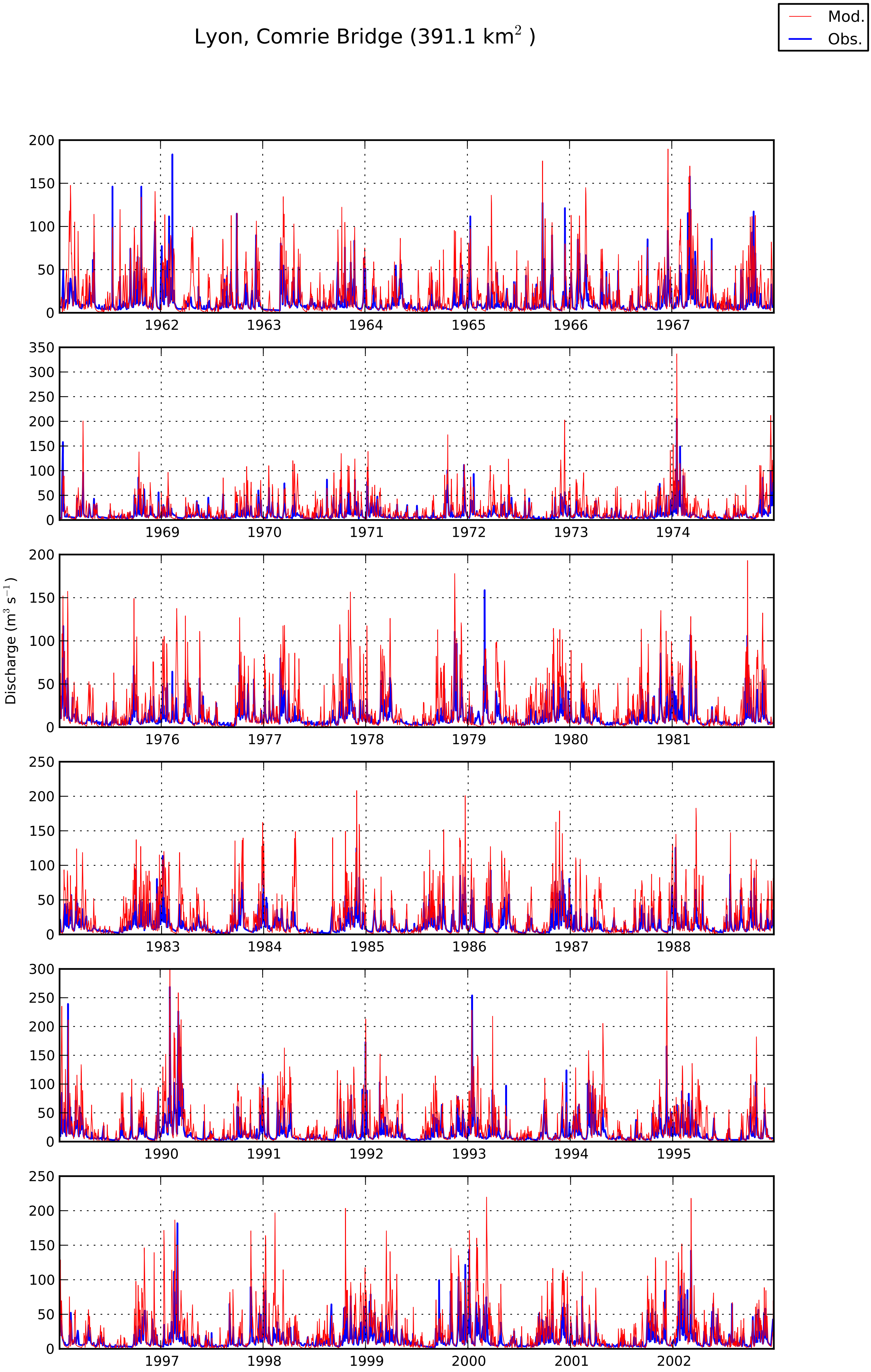
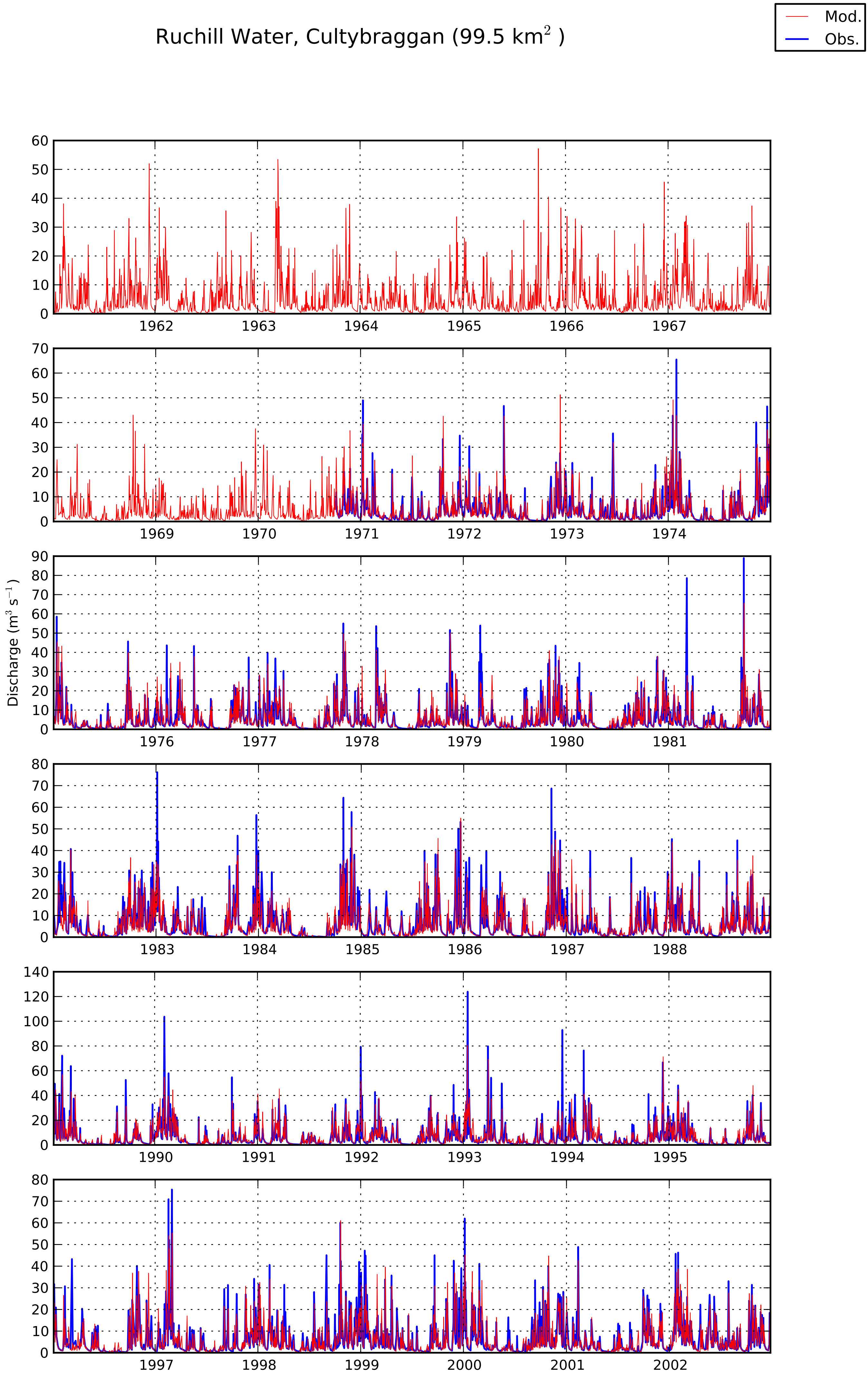

Lyon, Comrie Bridge (391.1 km^2)
Mod.
Obs.
Discharge (m^3 s^{-1})
1962 1963 1964 1965 1966 1967
1969 1970 1971 1972 1973 1974
1976 1977 1978 1979 1980 1981
1983 1984 1985 1986 1987 1988
1990 1991 1992 1993 1994 1995
1997 1998 1999 2000 2001 2002


Ruchill Water, Cultybraggan (99.5 km^2)
Mod.
Obs.
Discharge (m^3 s^{-1})
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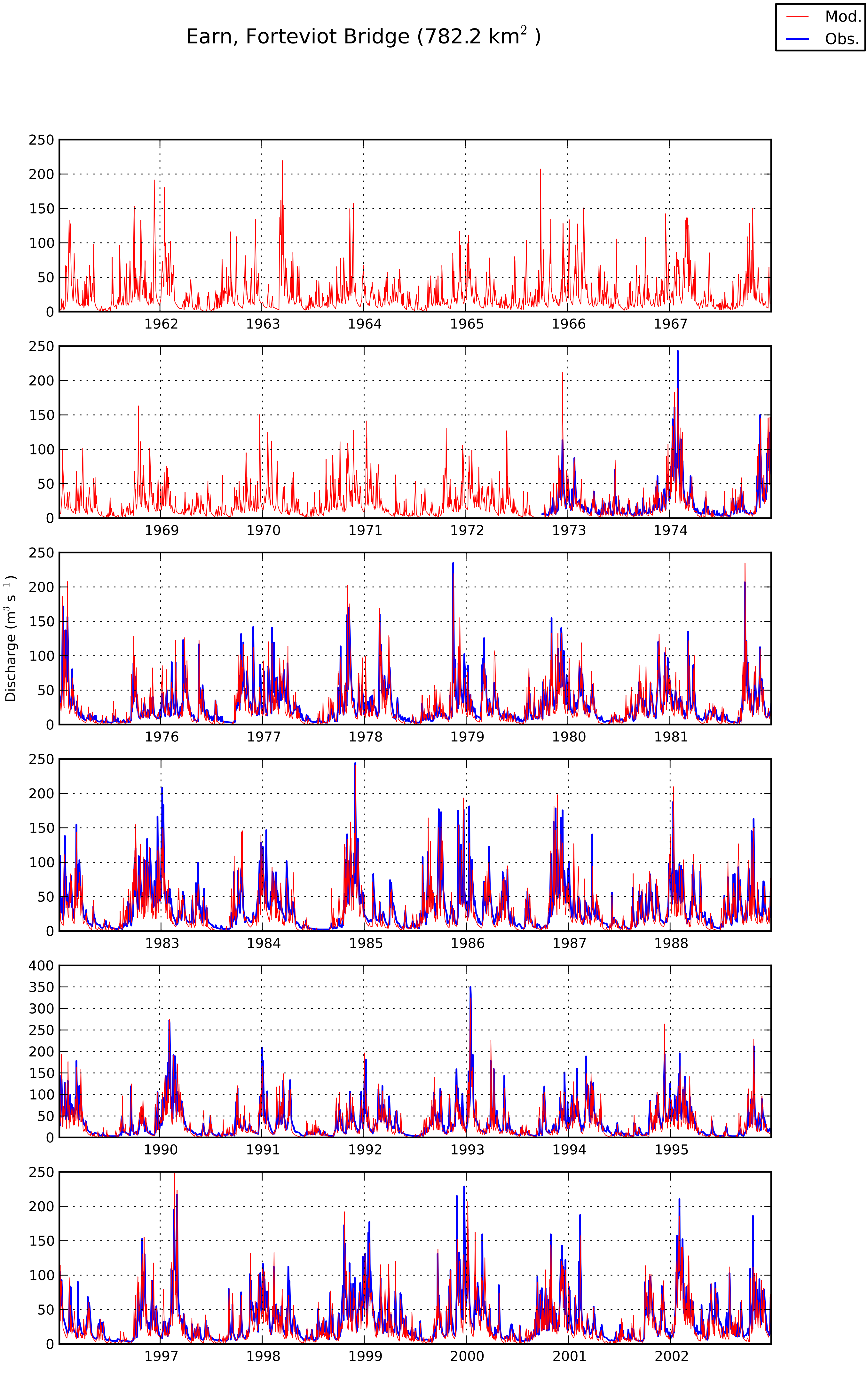
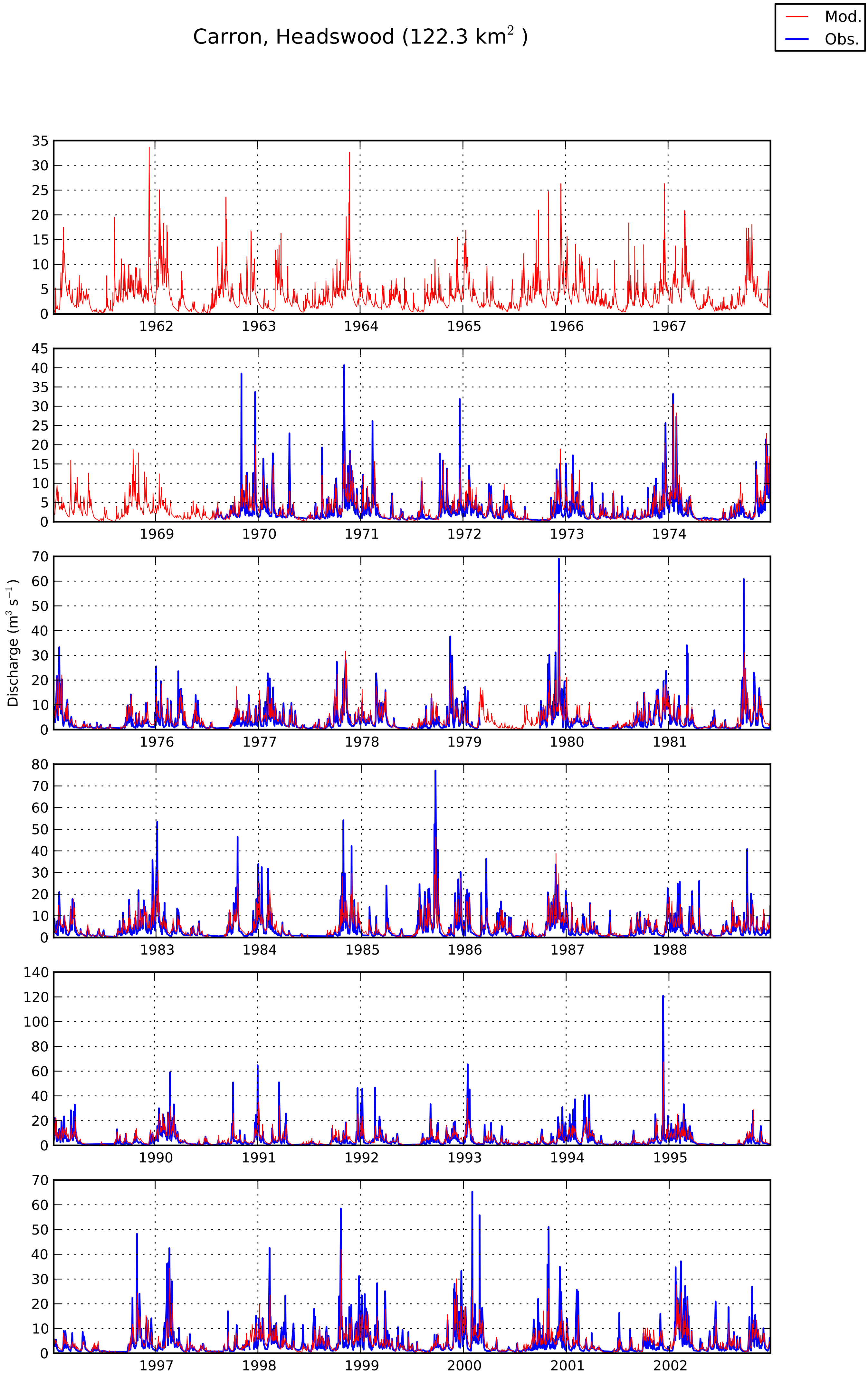
Earn, Forteviot Bridge (782.2 km^2)





Carron, Headswood (122.3 km^2)
Mod.
Obs.
Discharge (m^3 s^{-1})
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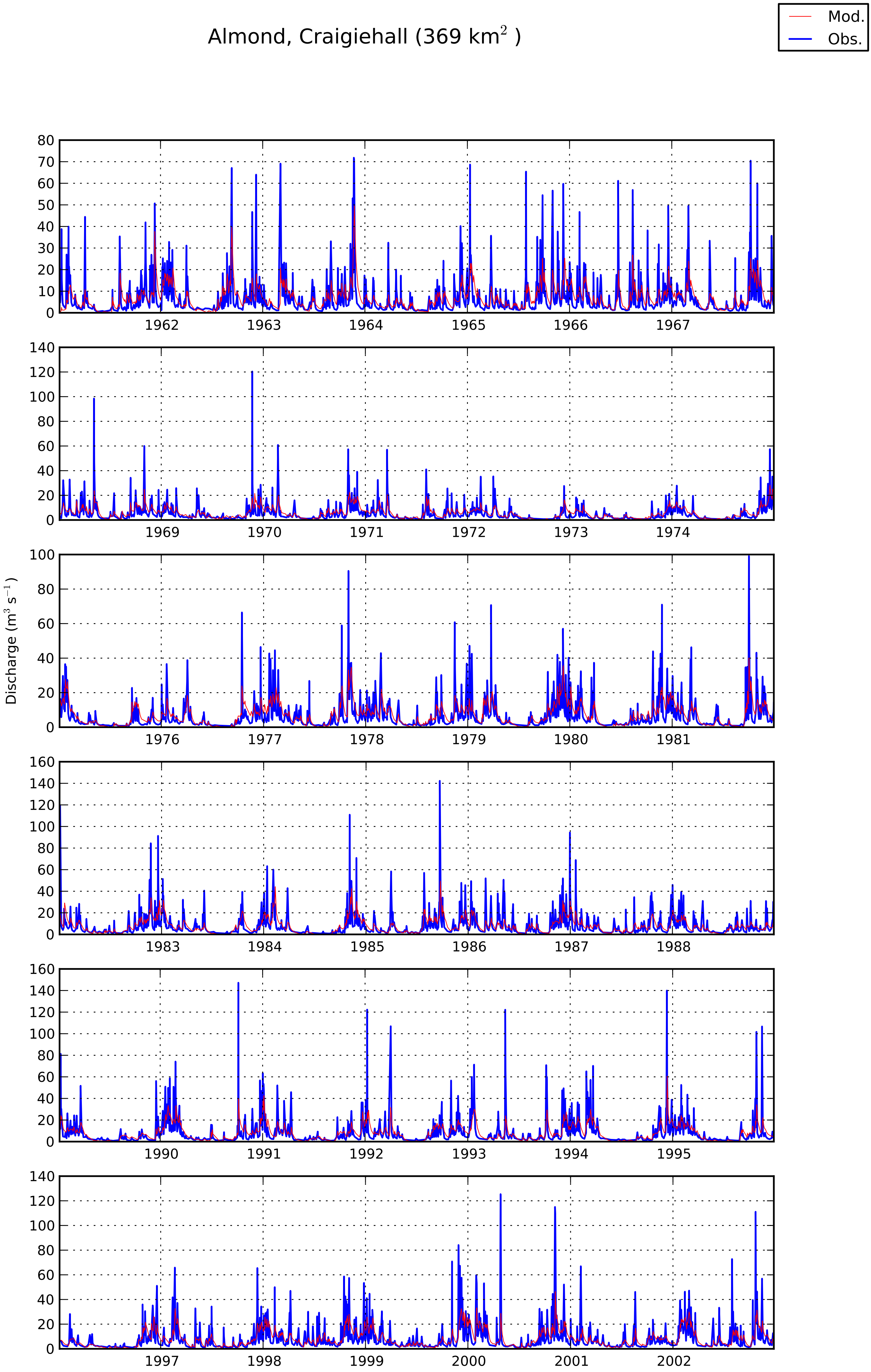

Almond, Craigiehall (369 km^2)
Mod.
Obs.
Discharge (m^3 s^{-1})
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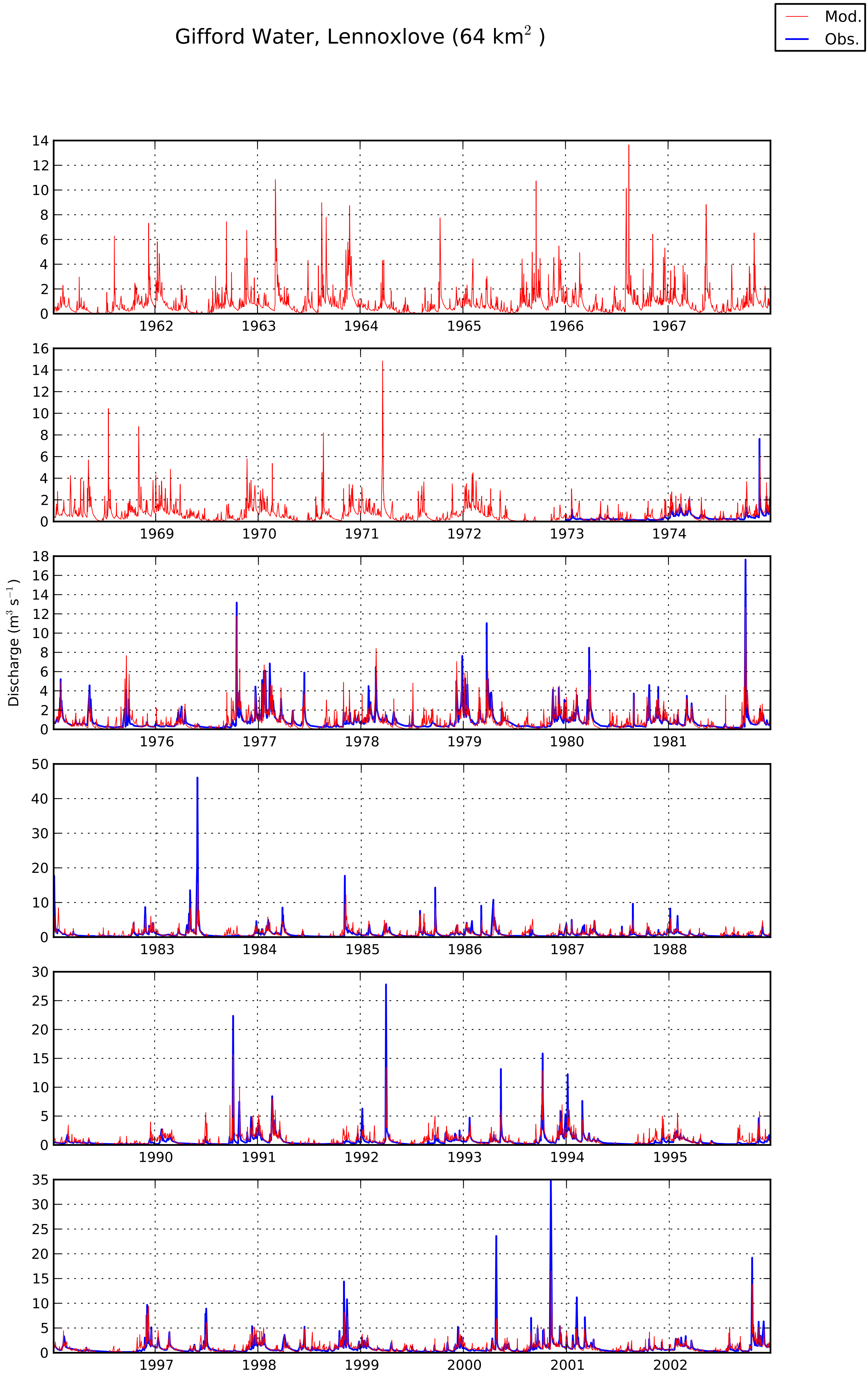

Gifford Water, Lennoxlove (64 km^2)
Mod.
Obs.
Discharge (m^3 s^{-1})
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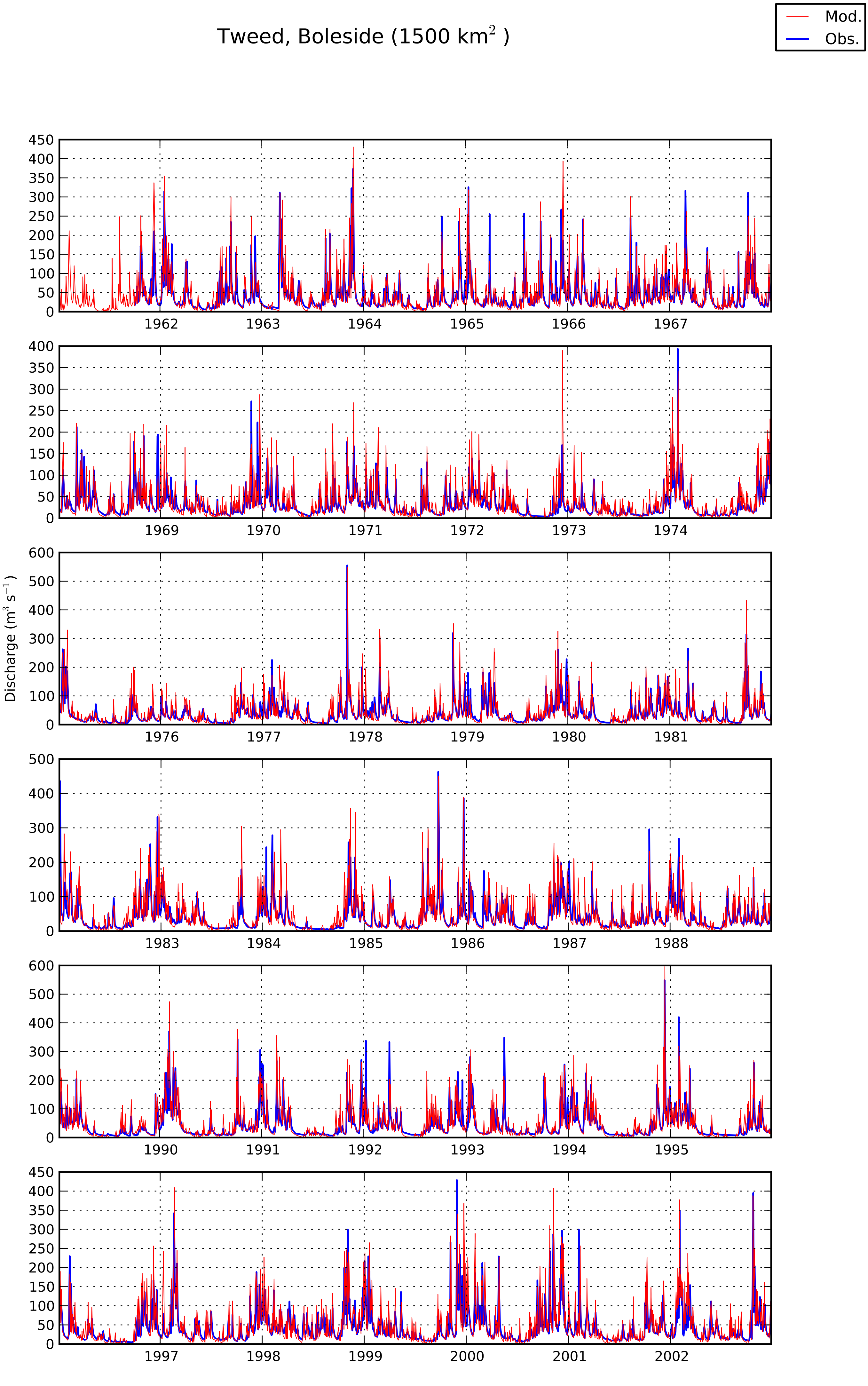

Tweed, Boleside (1500 km^2)
Mod.
Obs.
Discharge (m^3 s^{-1})
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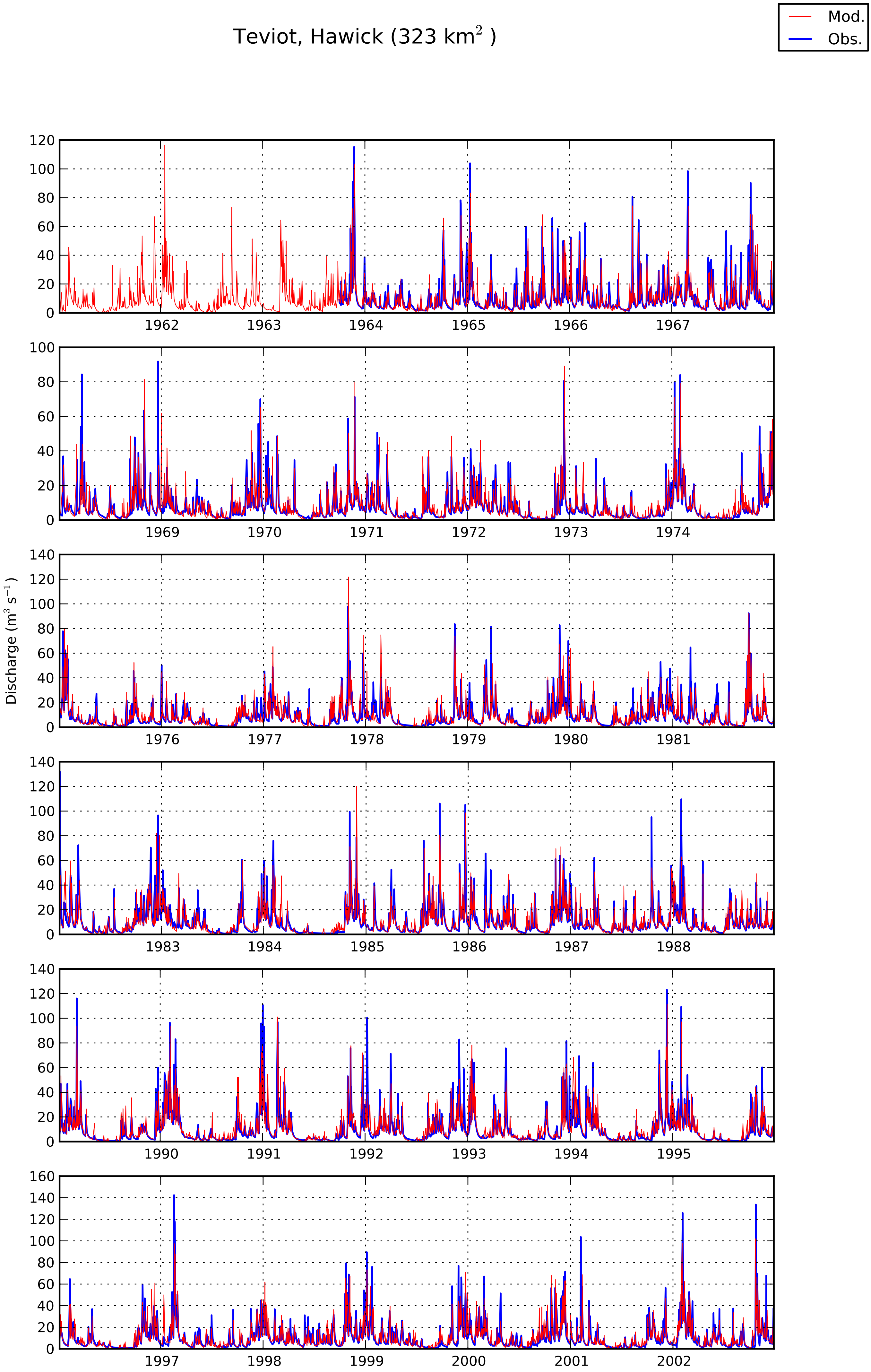
Teviot, Hawick (323 km^2)
Mod.
Obs.
Discharge (m^3 s^{-1})
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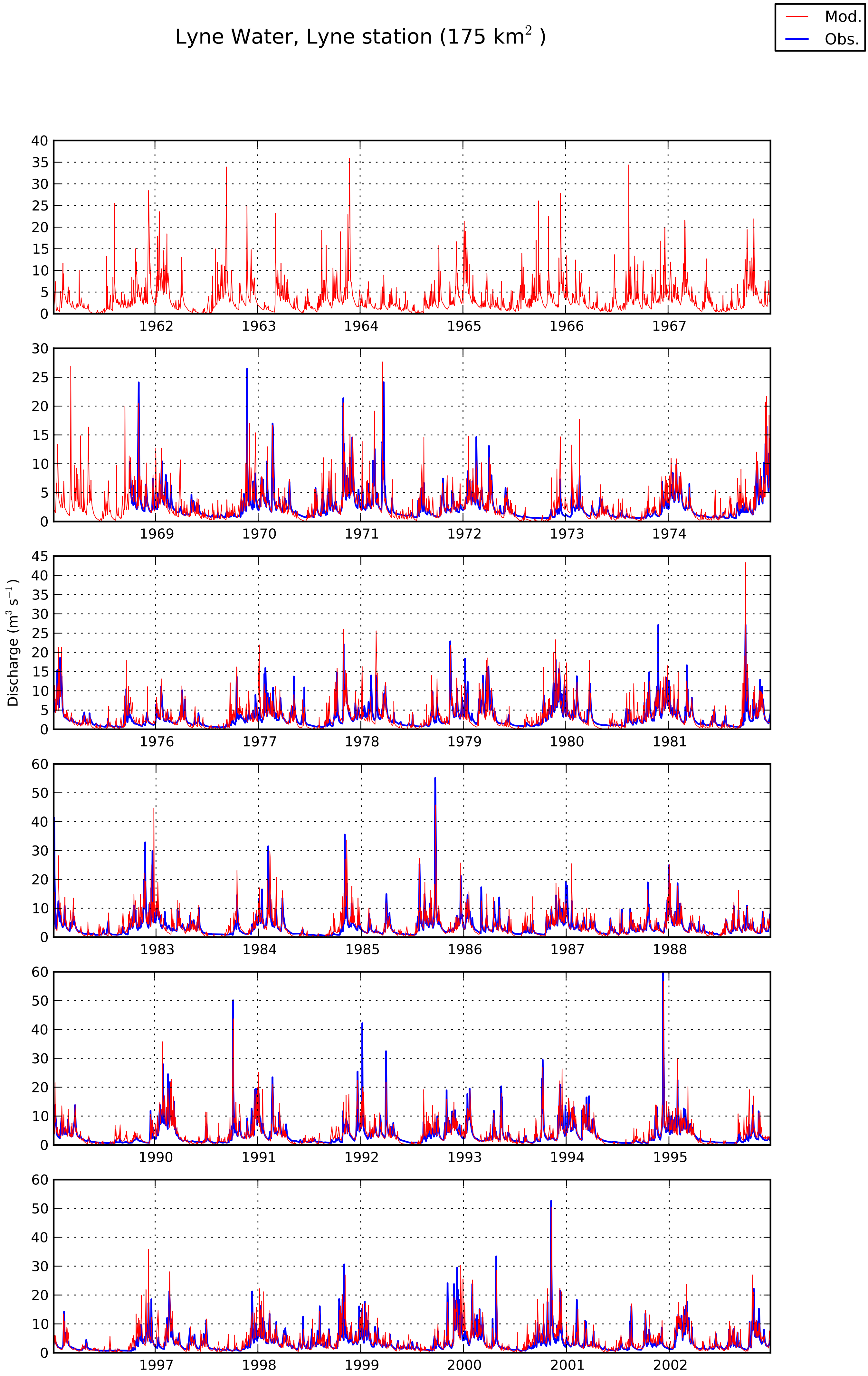

Mod.
Obs.
Lyne Water, Lyne station (175 km^2)
Discharge (m^3 s^{-1})
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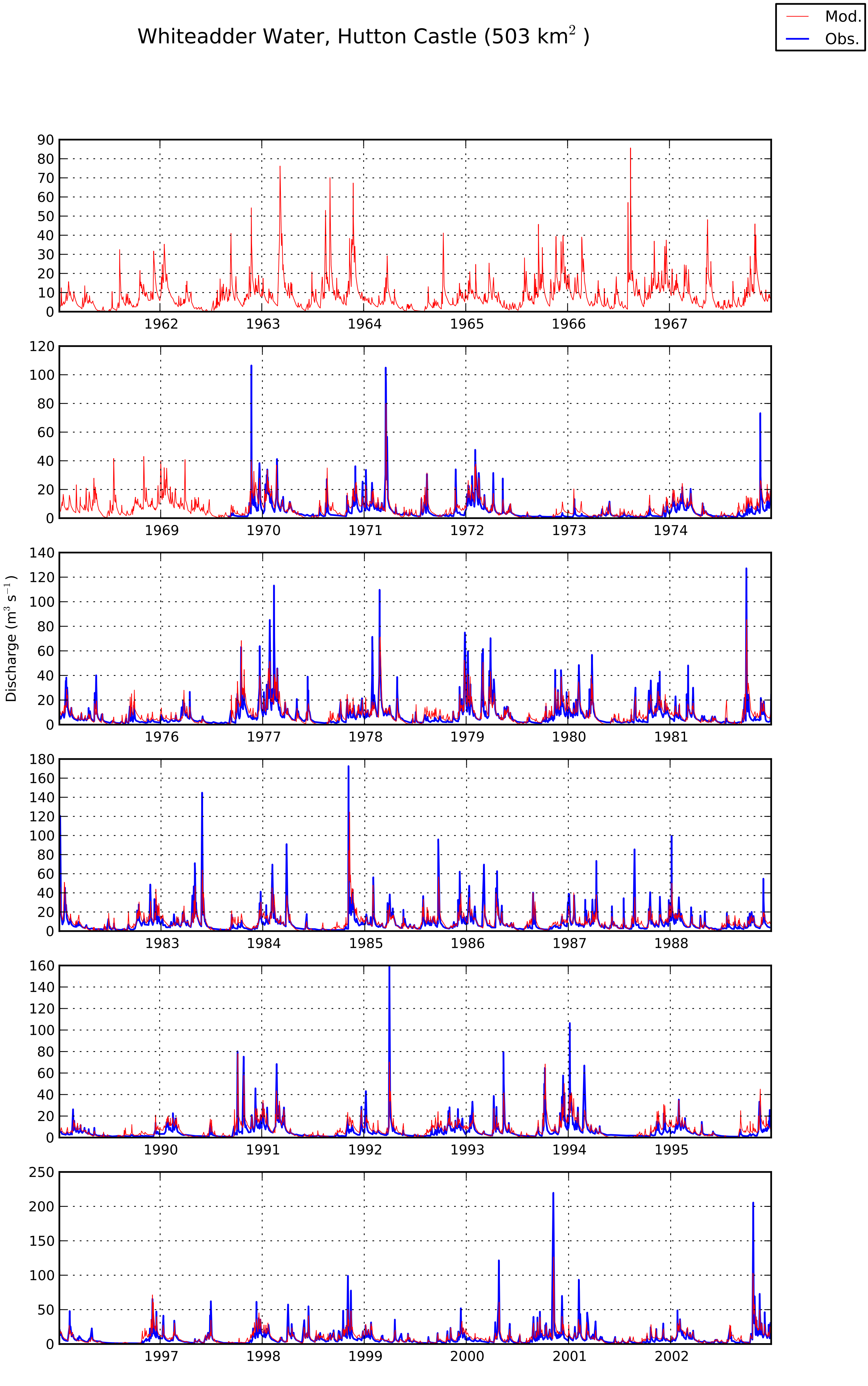
Whiteadder Water, Hutton Castle (503 km^2)
Mod.
Obs.
Discharge (m^3 s^{-1})
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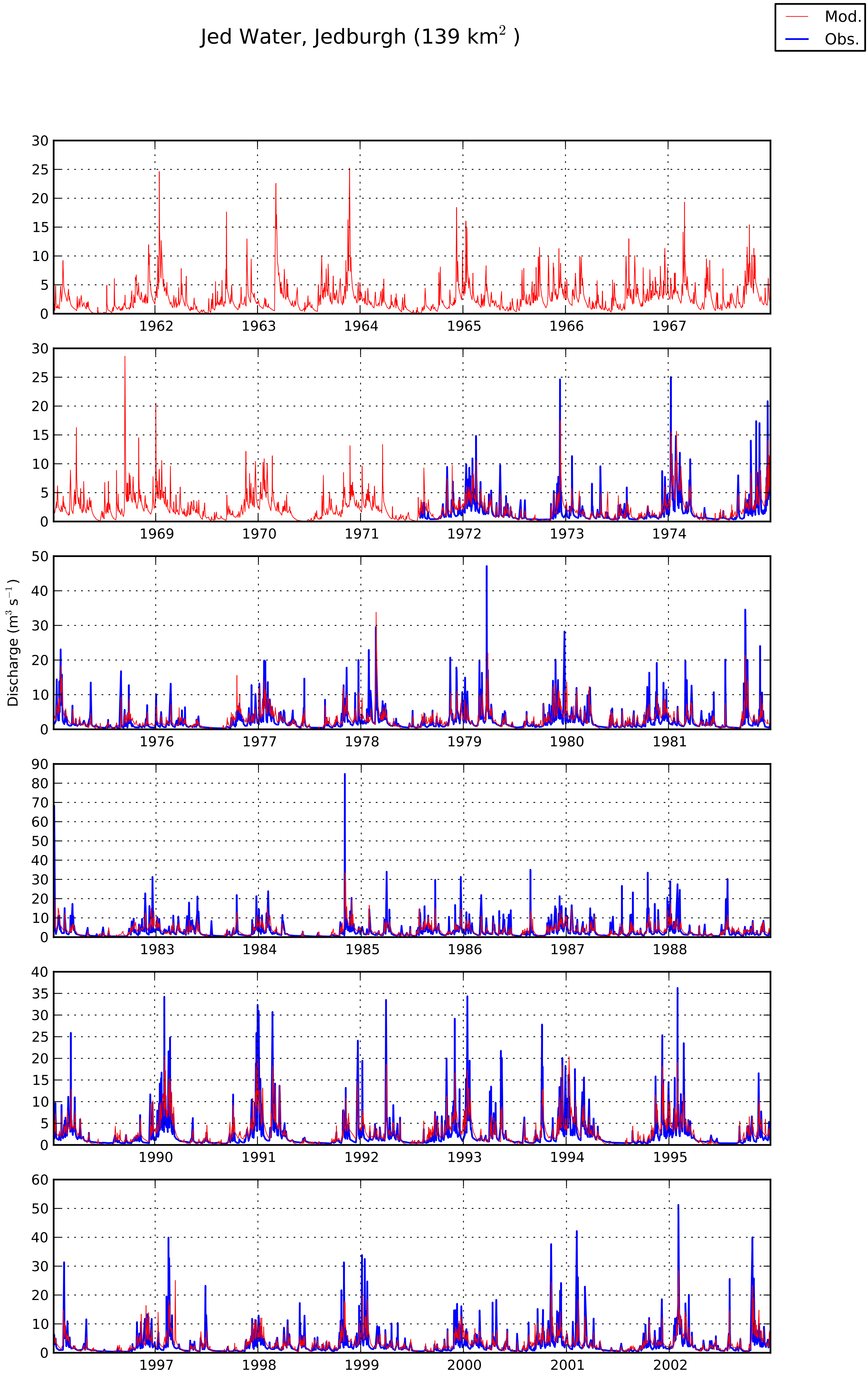

Jed Water, Jedburgh (139 km^2)
Mod.
Obs.
Discharge (m^3 s^{-1})
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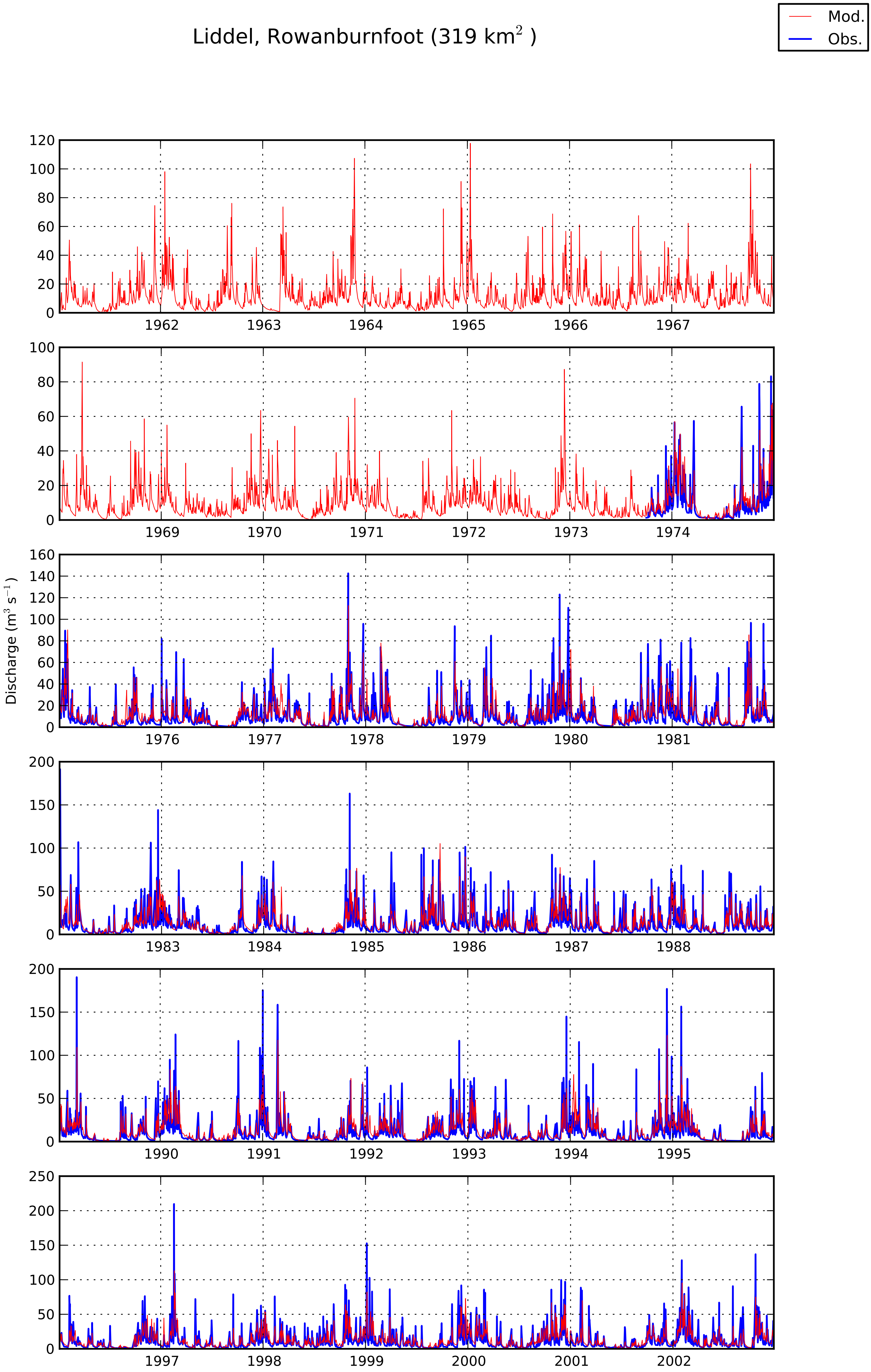
Liddel, Rowanburnfoot (319 km^2)
Mod.
Obs.
Discharge (m^3 s^{-1})
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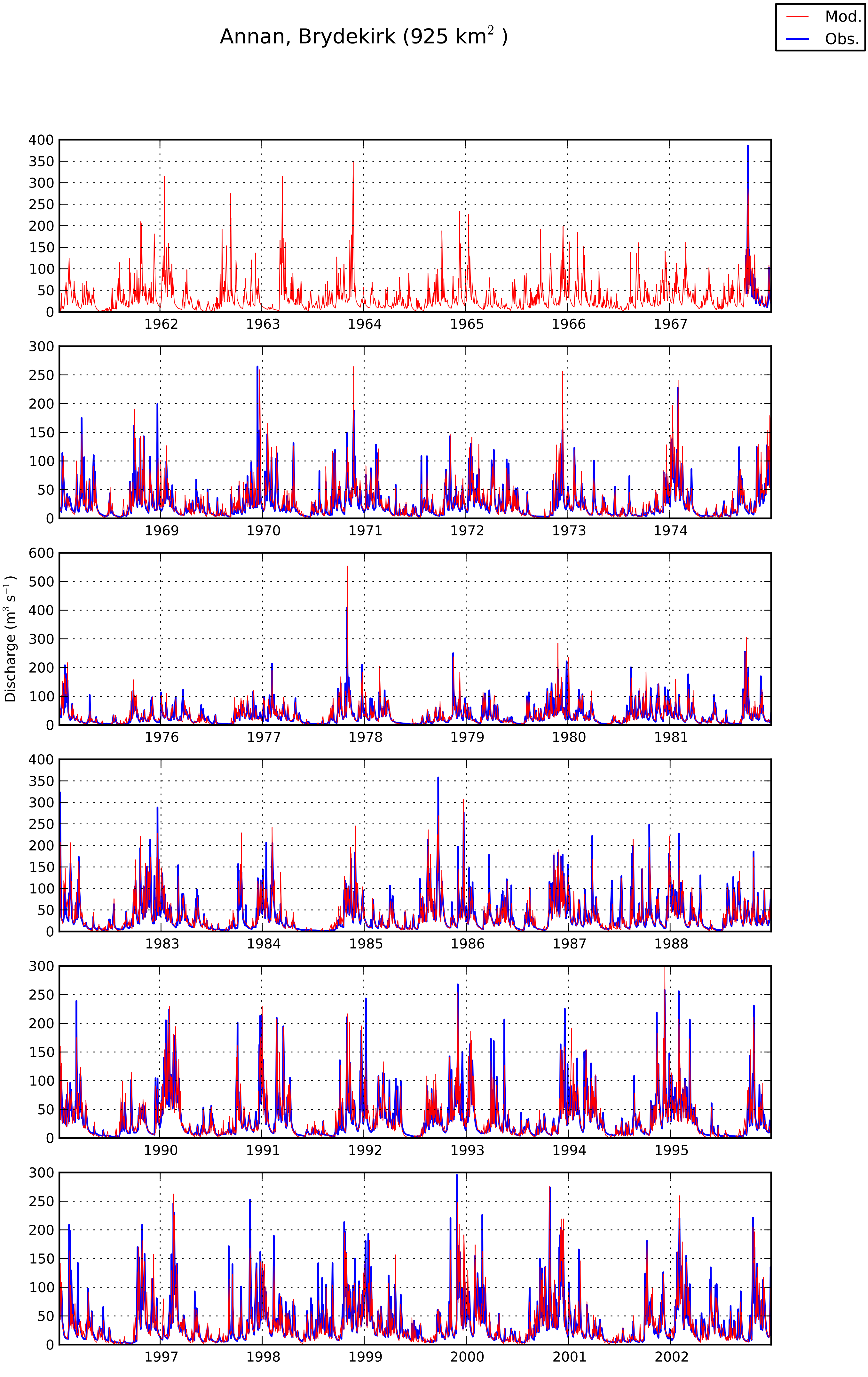

Annan, Brydekirk (925 km^2)
Mod.
Obs.
Discharge (m^3 s^{-1})
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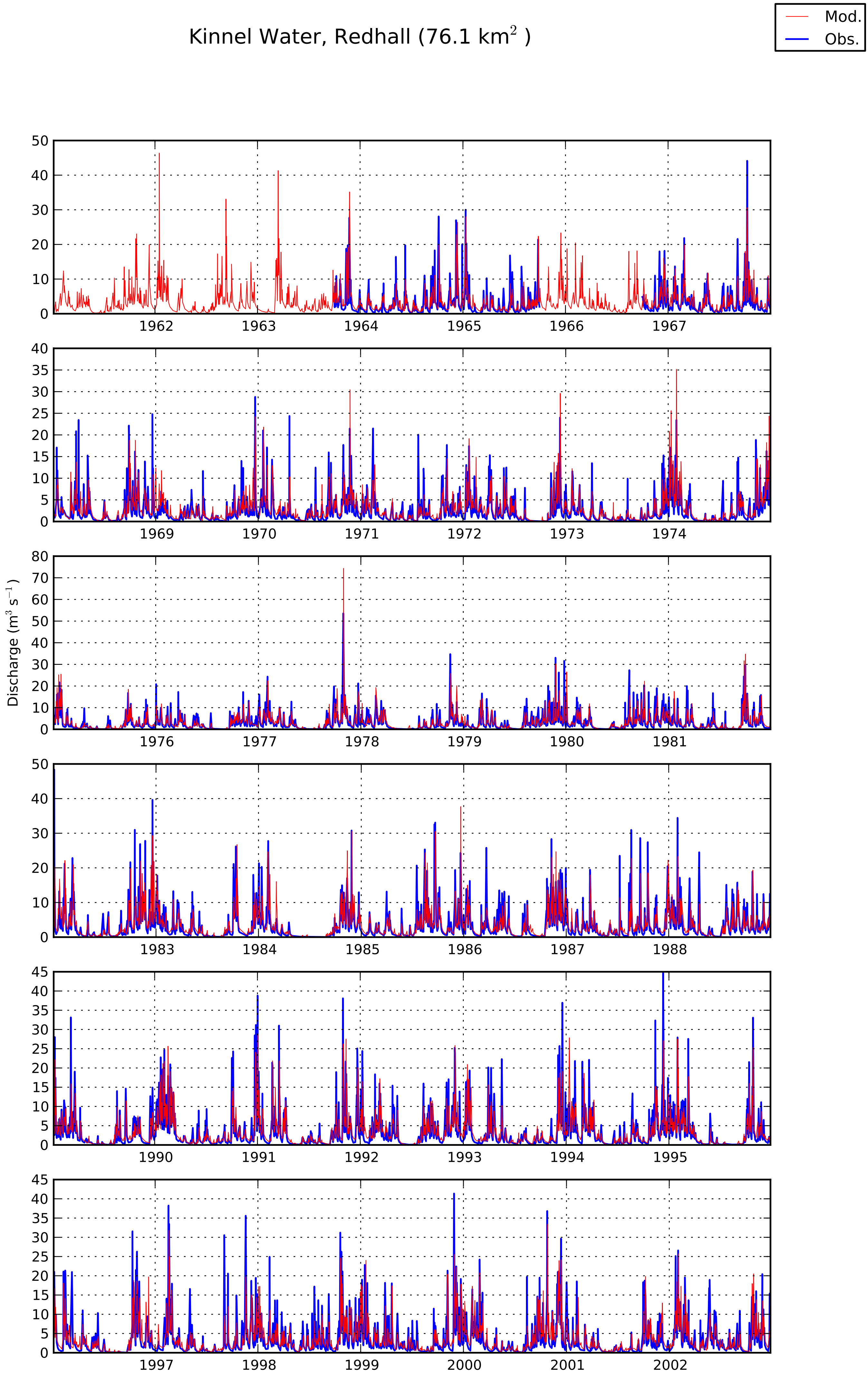
Kinnel Water, Redhall (76.1 km^2)
Mod.
Obs.
Discharge (m^3 s^{-1})
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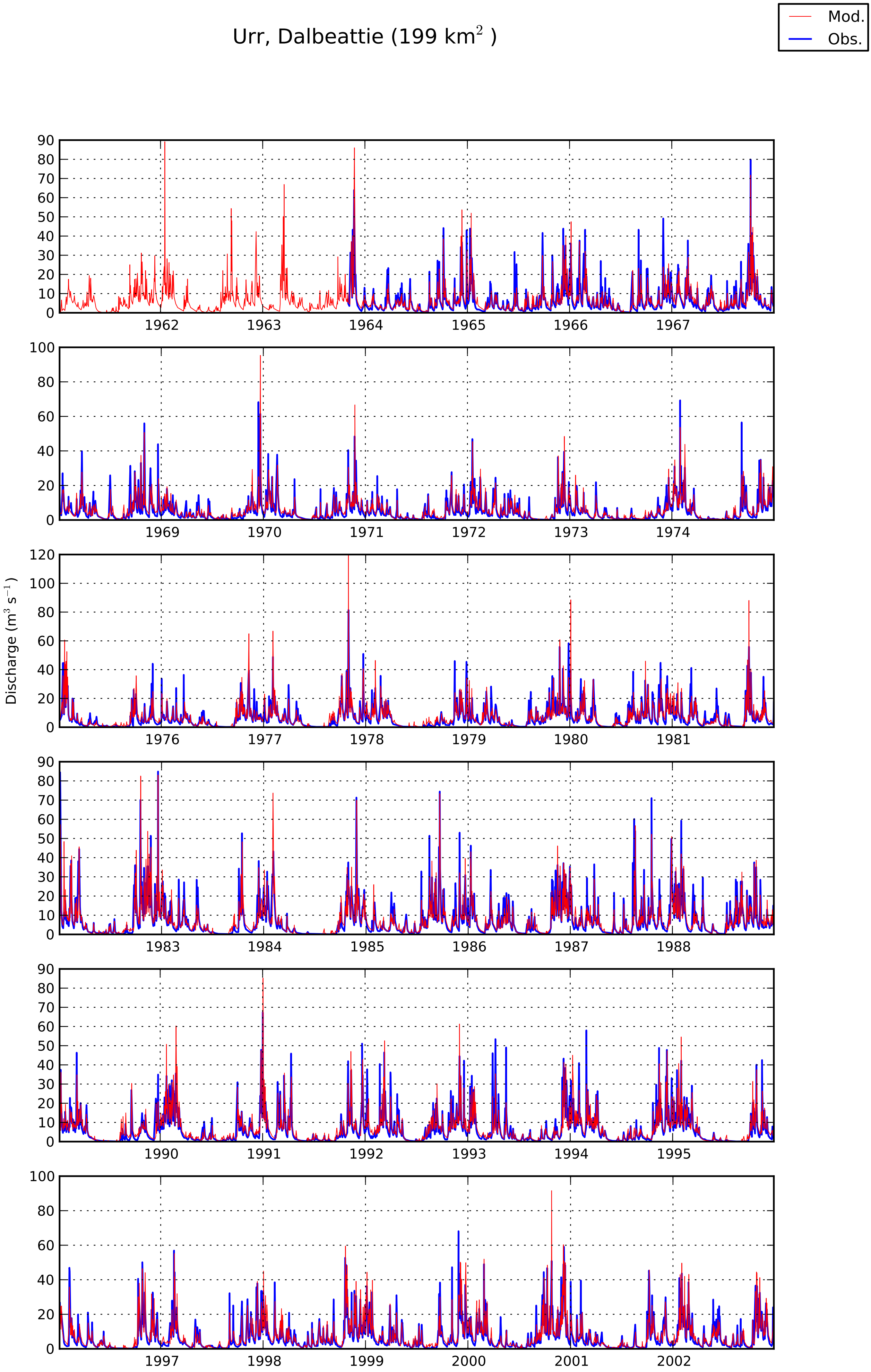

Urr, Dalbeattie (199 km^2)
Mod.
Obs.
Discharge (m^3 s^{-1})
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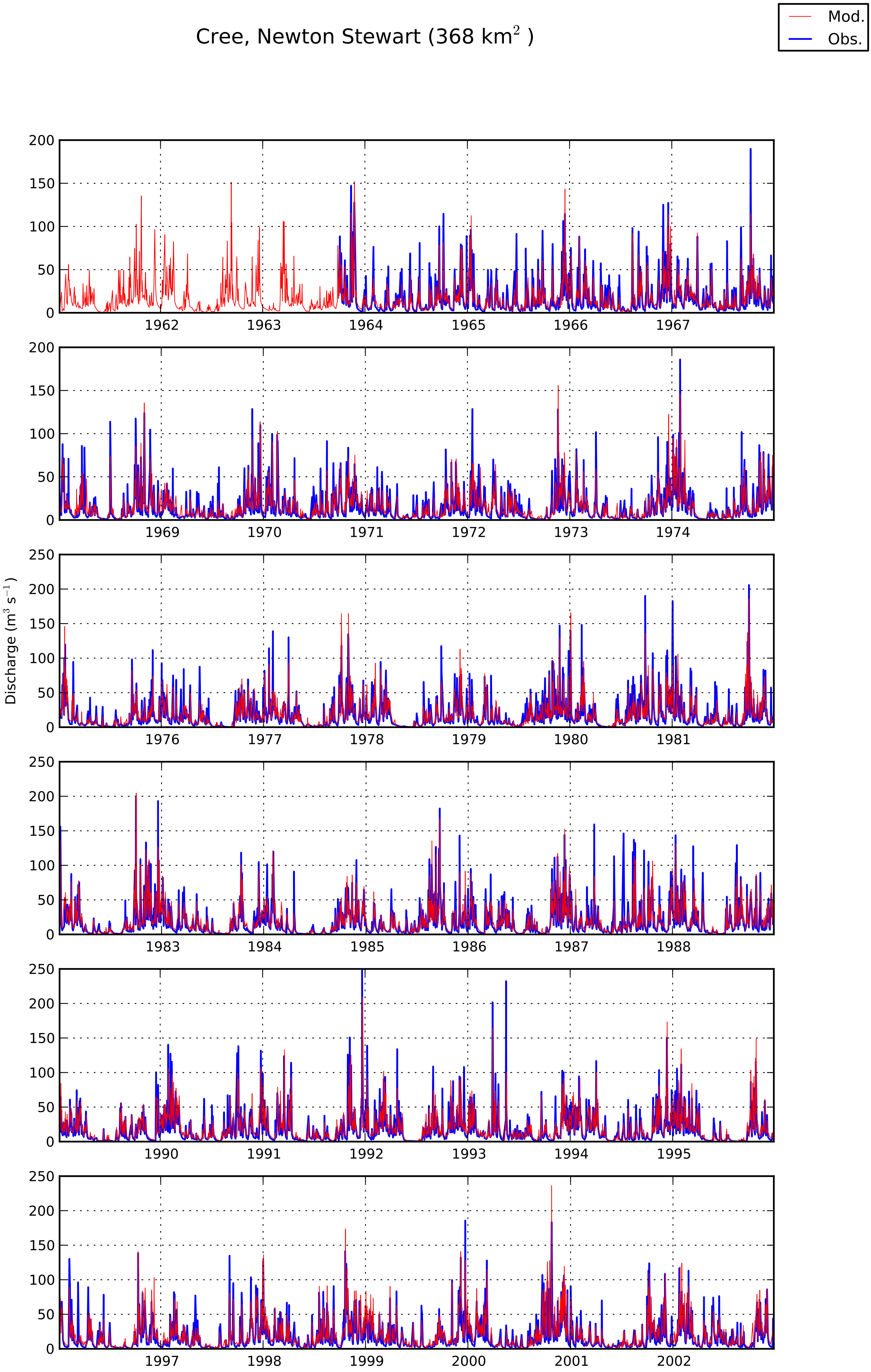

Cree, Newton Stewart (368 km²)
Mod.
Obs.
Discharge (m³ s⁻¹)
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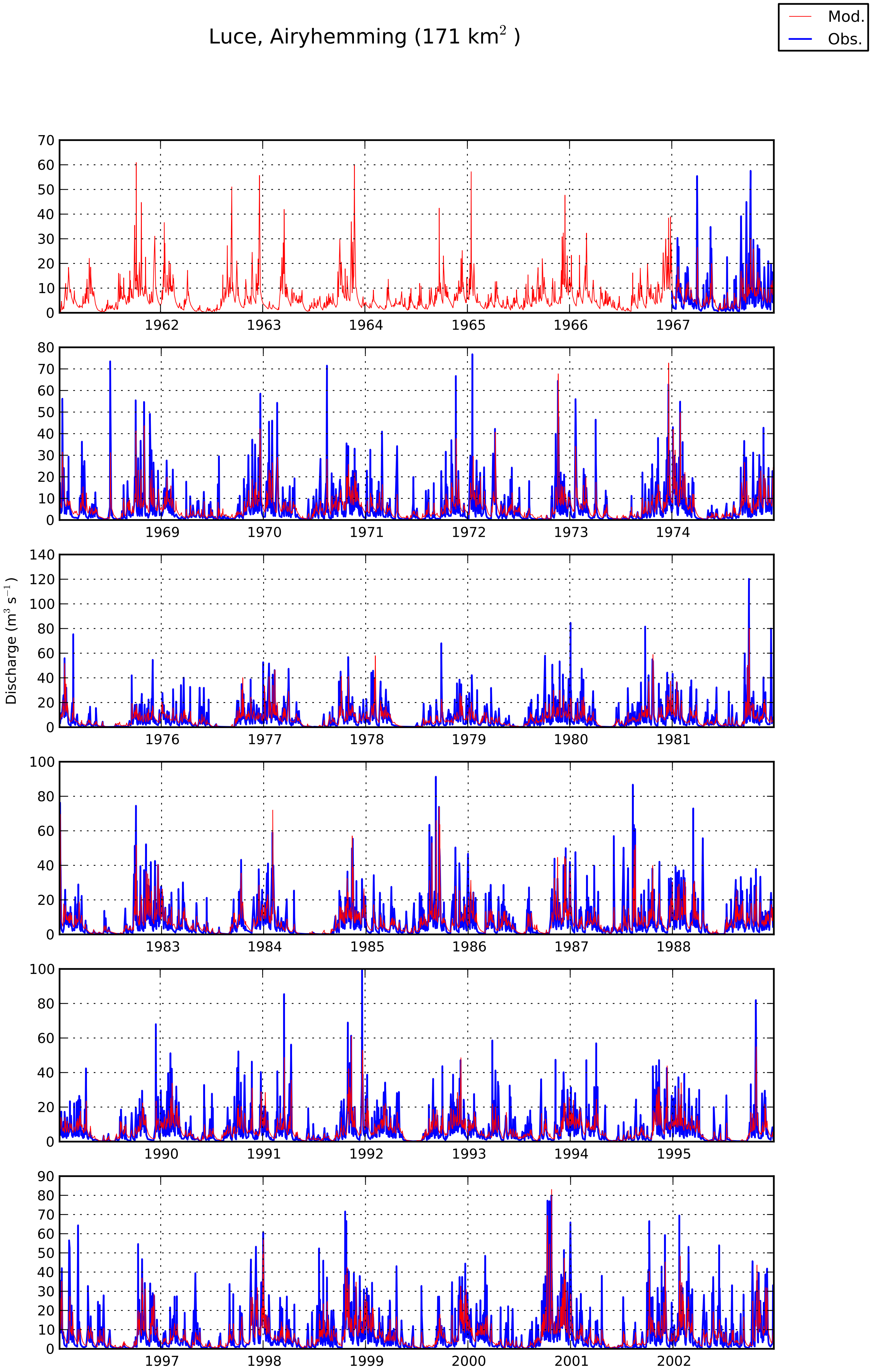
Luce, Airyhemming (171 km^2)
Mod.
Obs.
Discharge (m^3 s^{-1})
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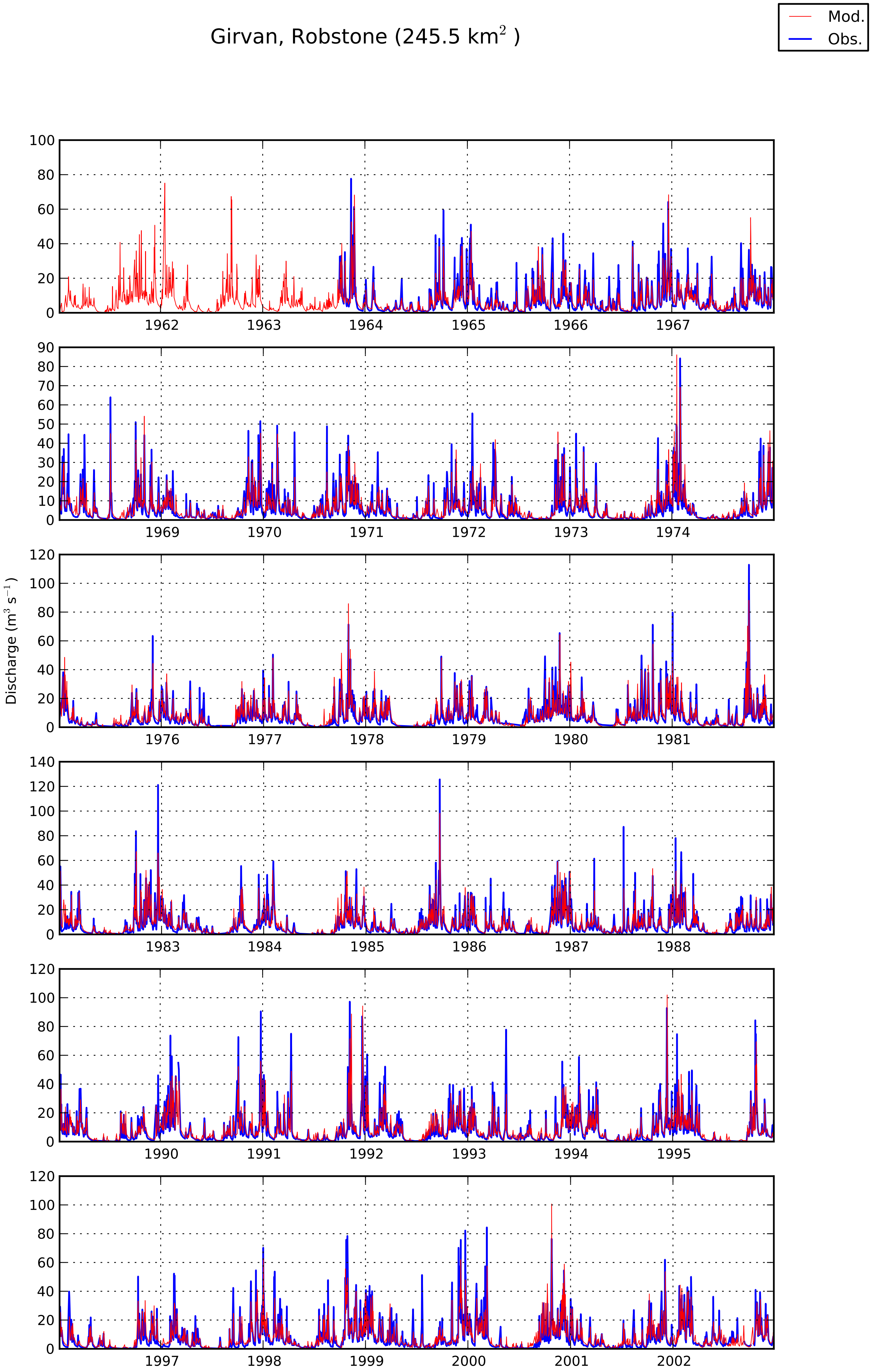
Girvan, Robstone (245.5 km^2)
Mod.
Obs.
Discharge (m^3 s^{-1})
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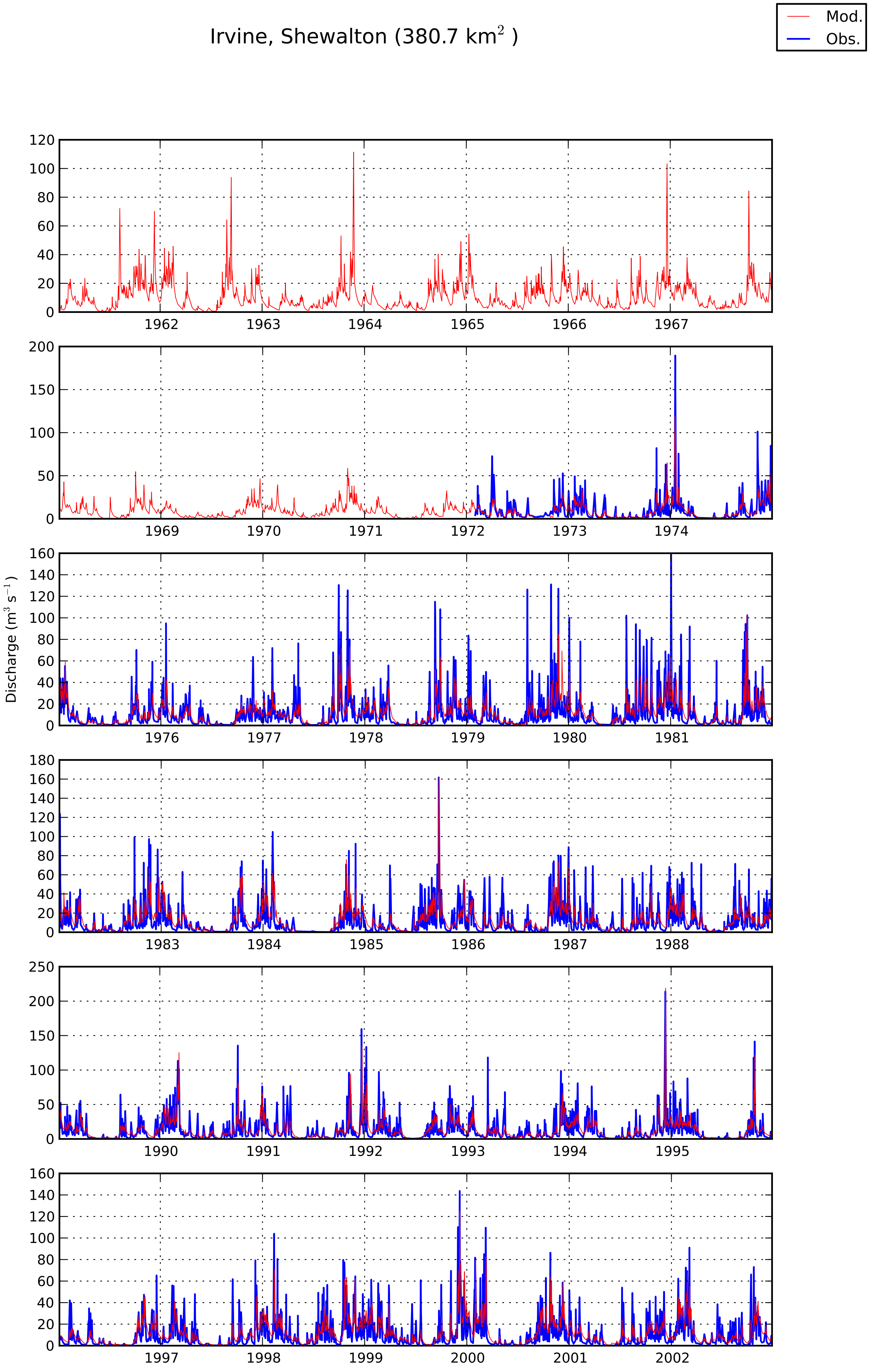
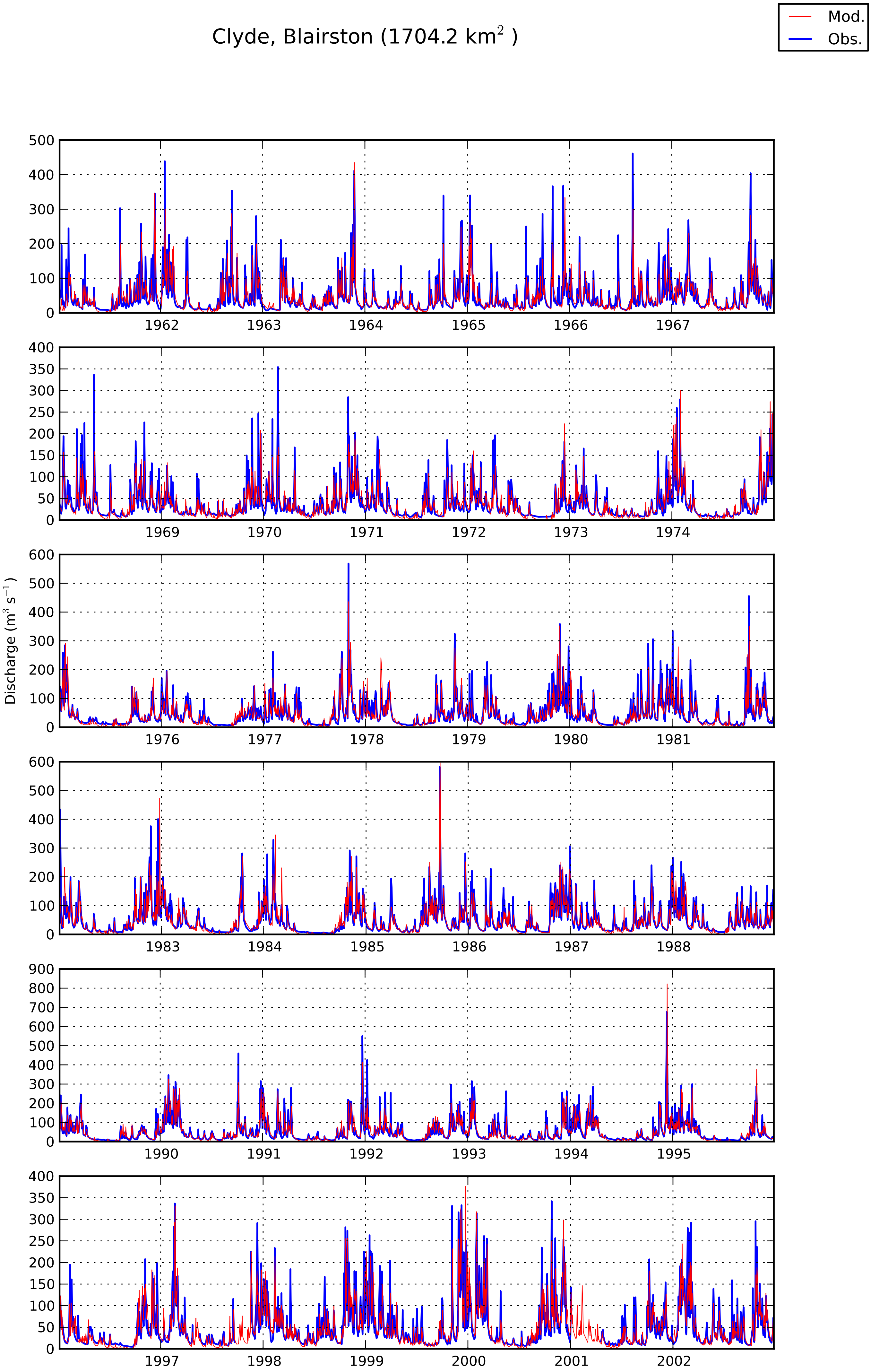


Irvine, Shewalton (380.7 km^2)
Mod.
Obs.
Discharge (m^3 s^{-1})
1962 1963 1964 1965 1966 1967
1969 1970 1971 1972 1973 1974
1976 1977 1978 1979 1980 1981
1983 1984 1985 1986 1987 1988
1990 1991 1992 1993 1994 1995
1997 1998 1999 2000 2001 2002



Clyde, Blairston (1704.2 km^2)
Mod.
Obs.
Discharge (m^3 s^{-1})
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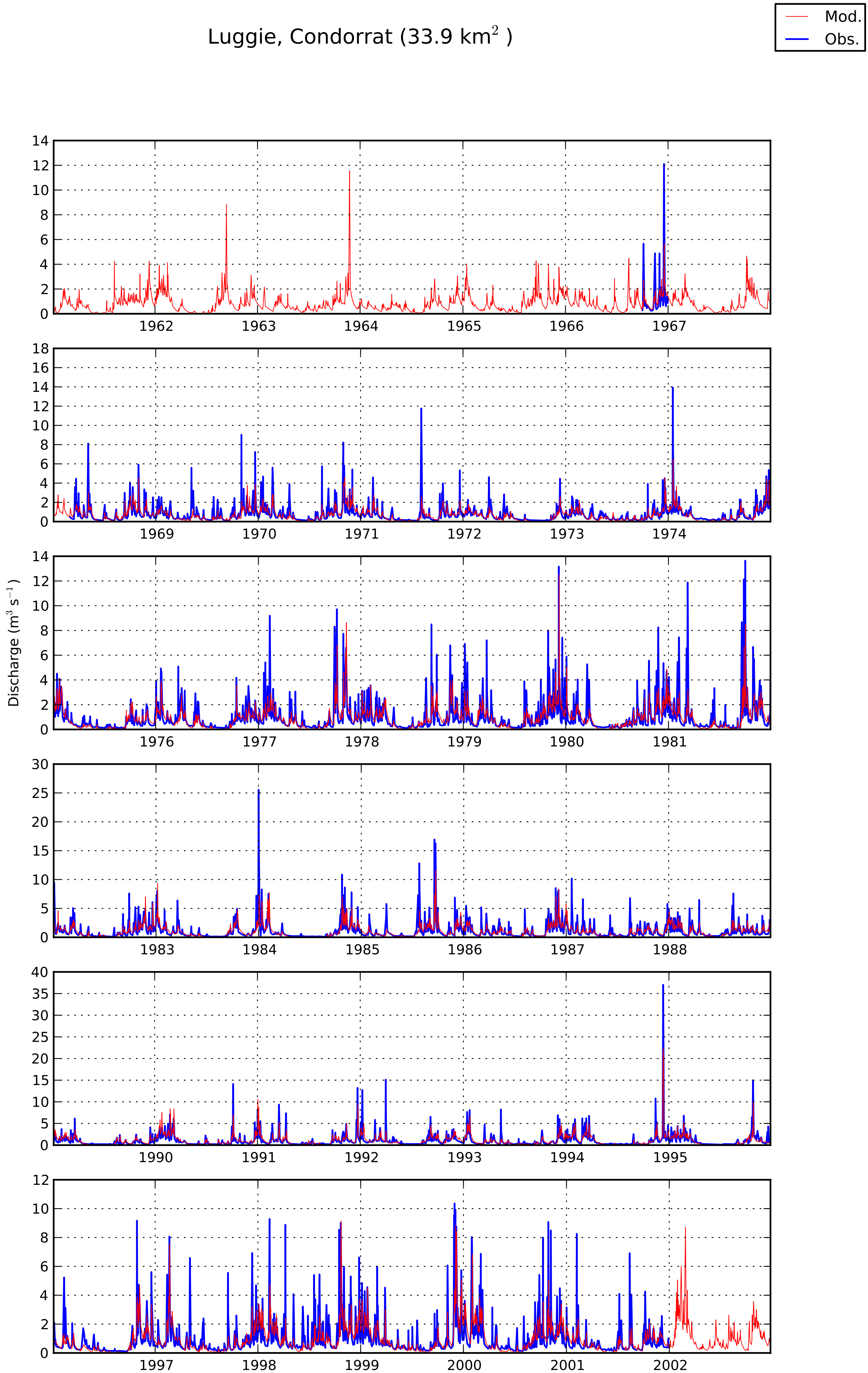
Luggie, Condorrat (33.9 km^2)
Mod.
Obs.
Discharge (m^3 s^{-1})
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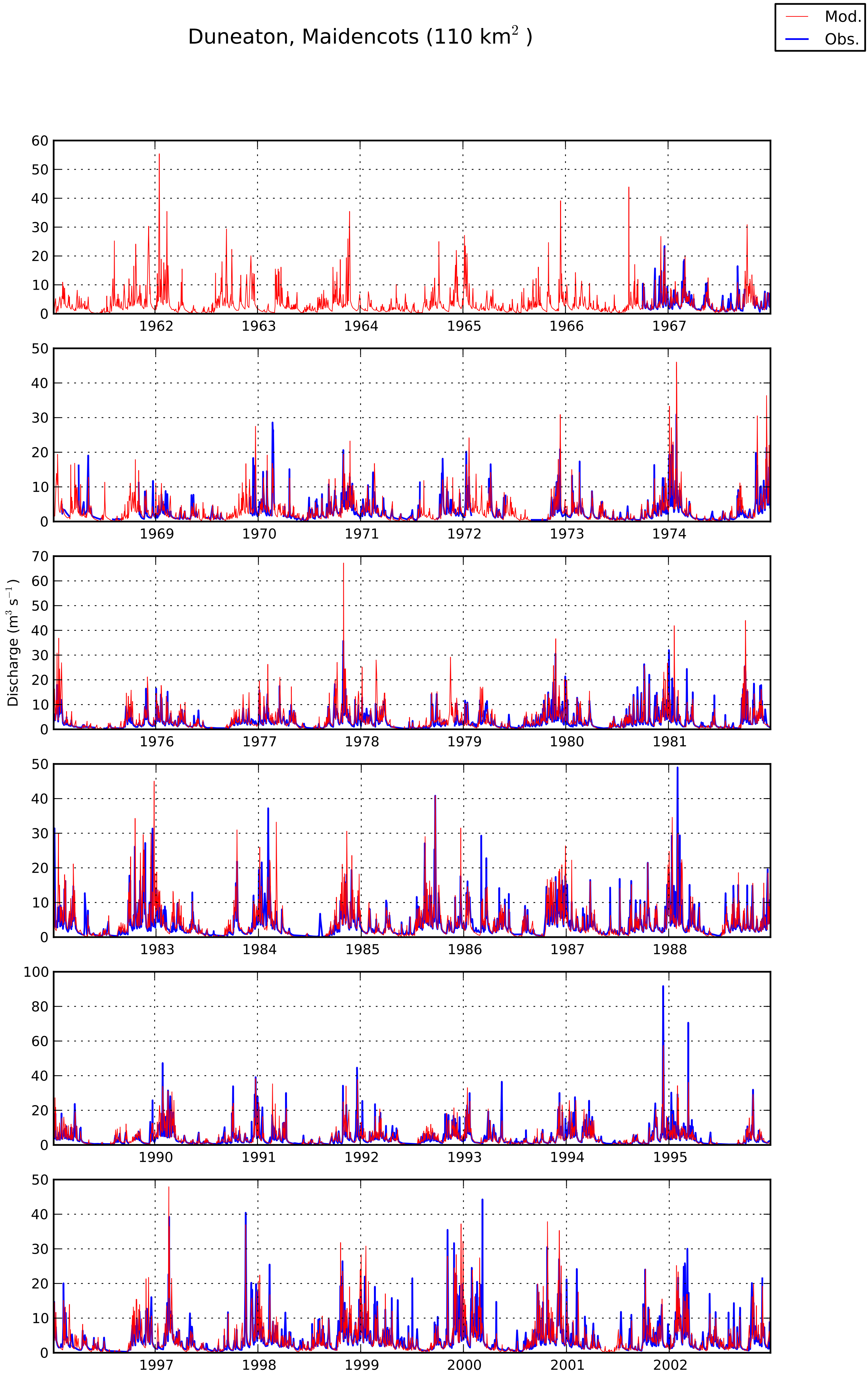
Duneaton, Maidencots (110 km^2)
Mod.
Obs.
Discharge (m^3 s^{-1})
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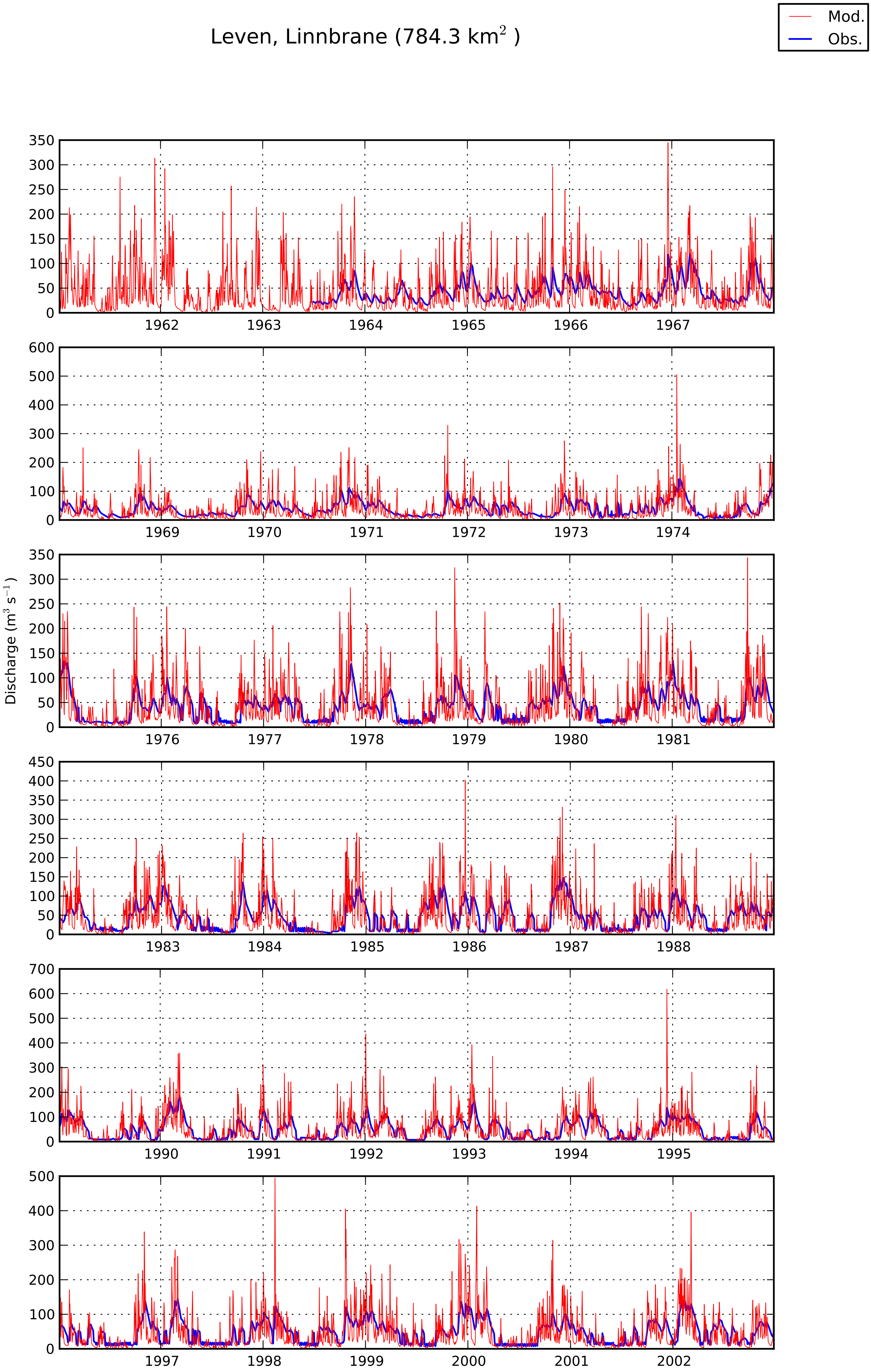
Leven, Linnbrane (784.3 km^2)
Mod.
Obs.
Discharge (m^3 s^{-1})
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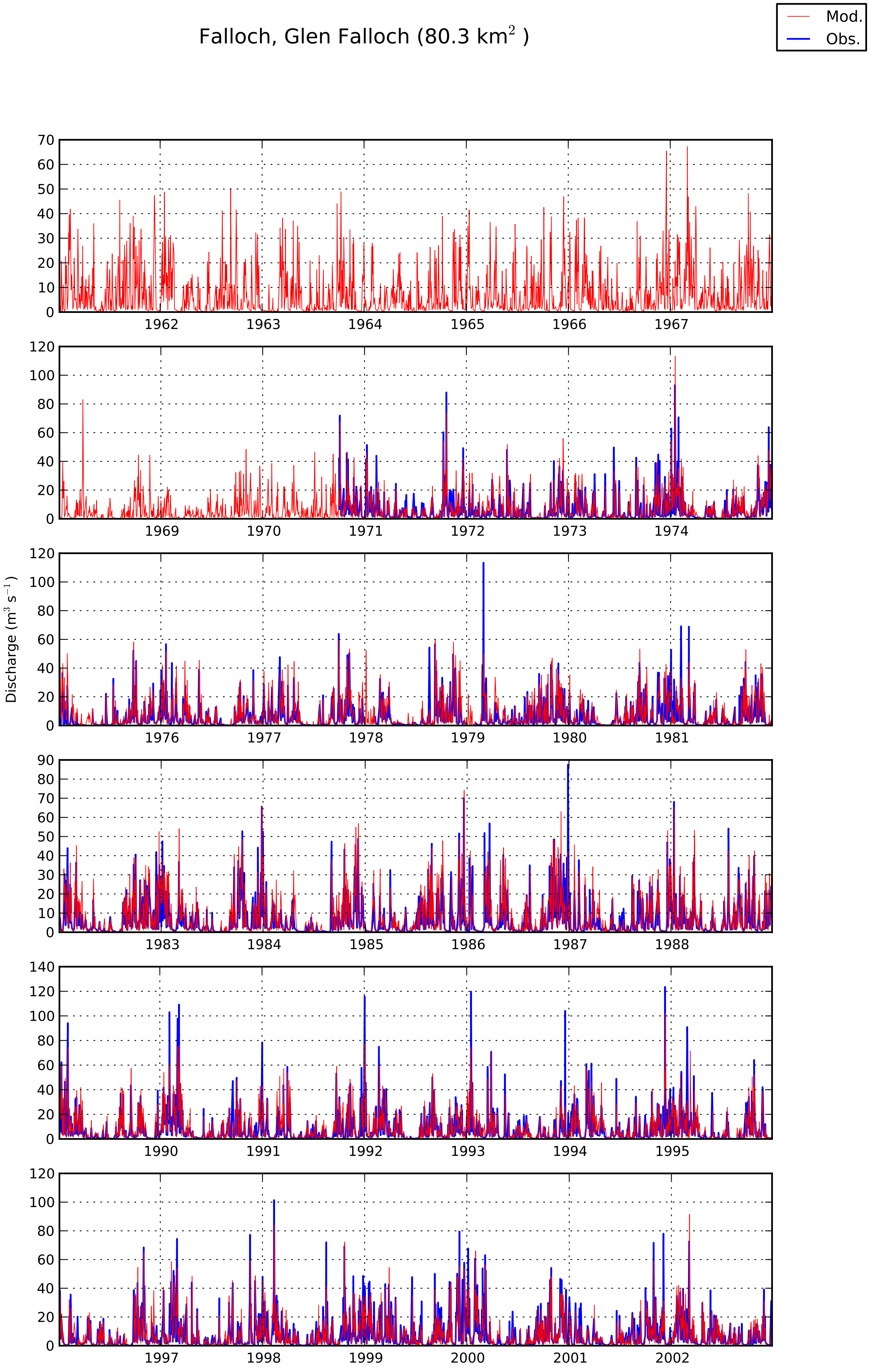
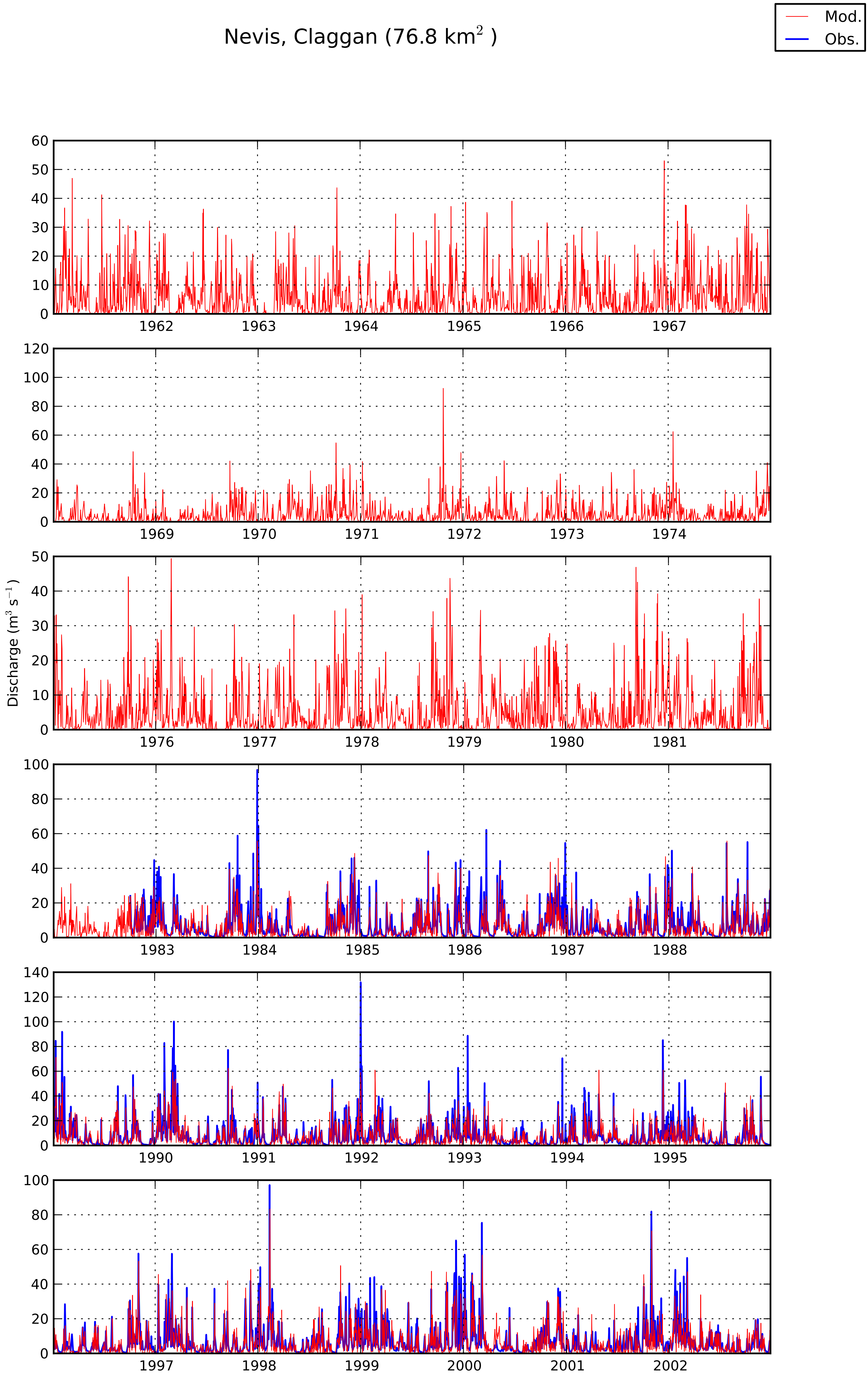


Falloch, Glen Falloch (80.3 km^2)
Mod.
Obs.
Discharge (m^3 s^{-1})


Nevis, Claggan (76.8 km^2)
Mod.
Obs.
Discharge (m^3 s^{-1})
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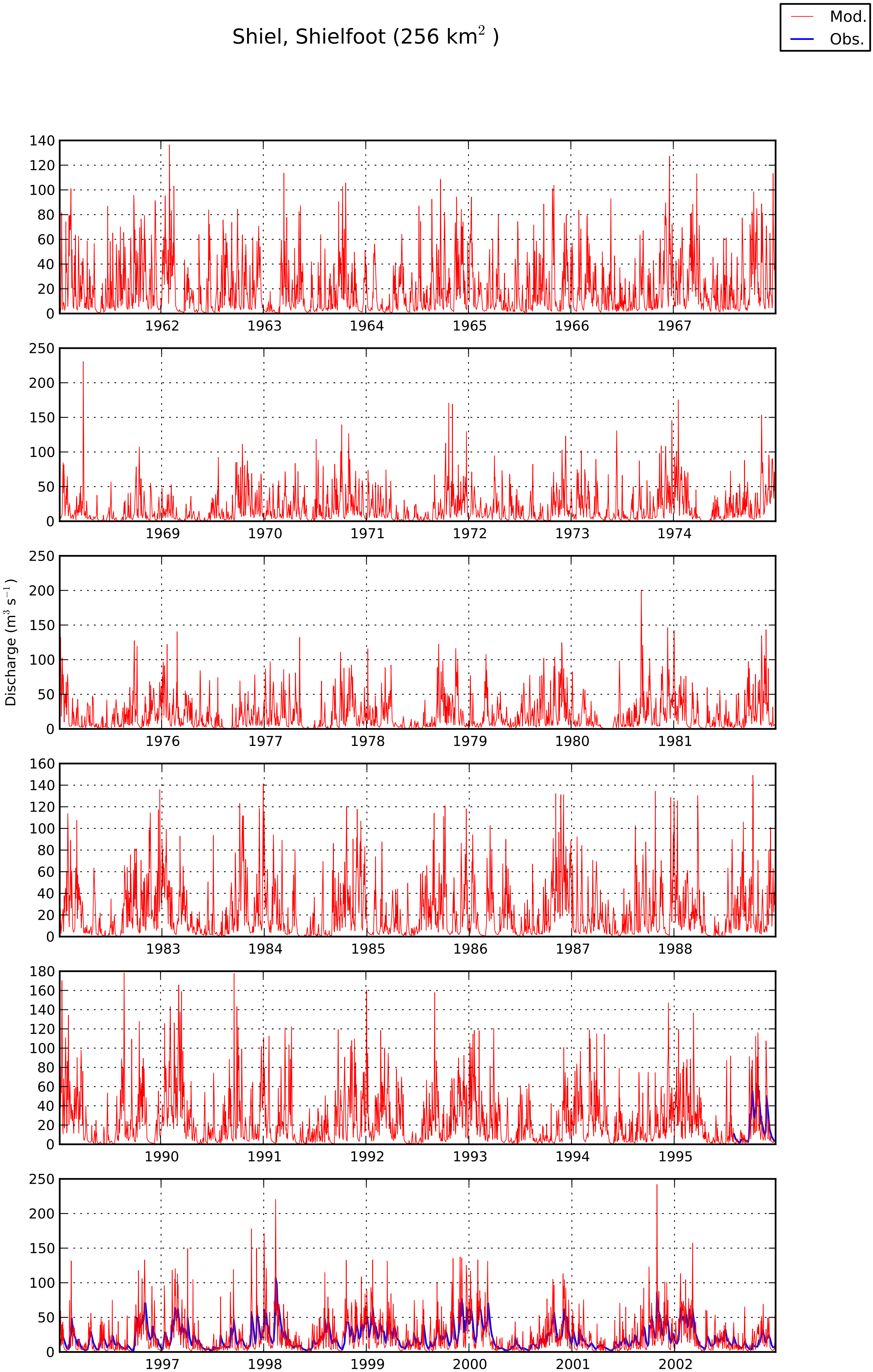

Shiel, Shielfoot (256 km^2)
Mod.
Obs.
Discharge (m^3 s^{-1})
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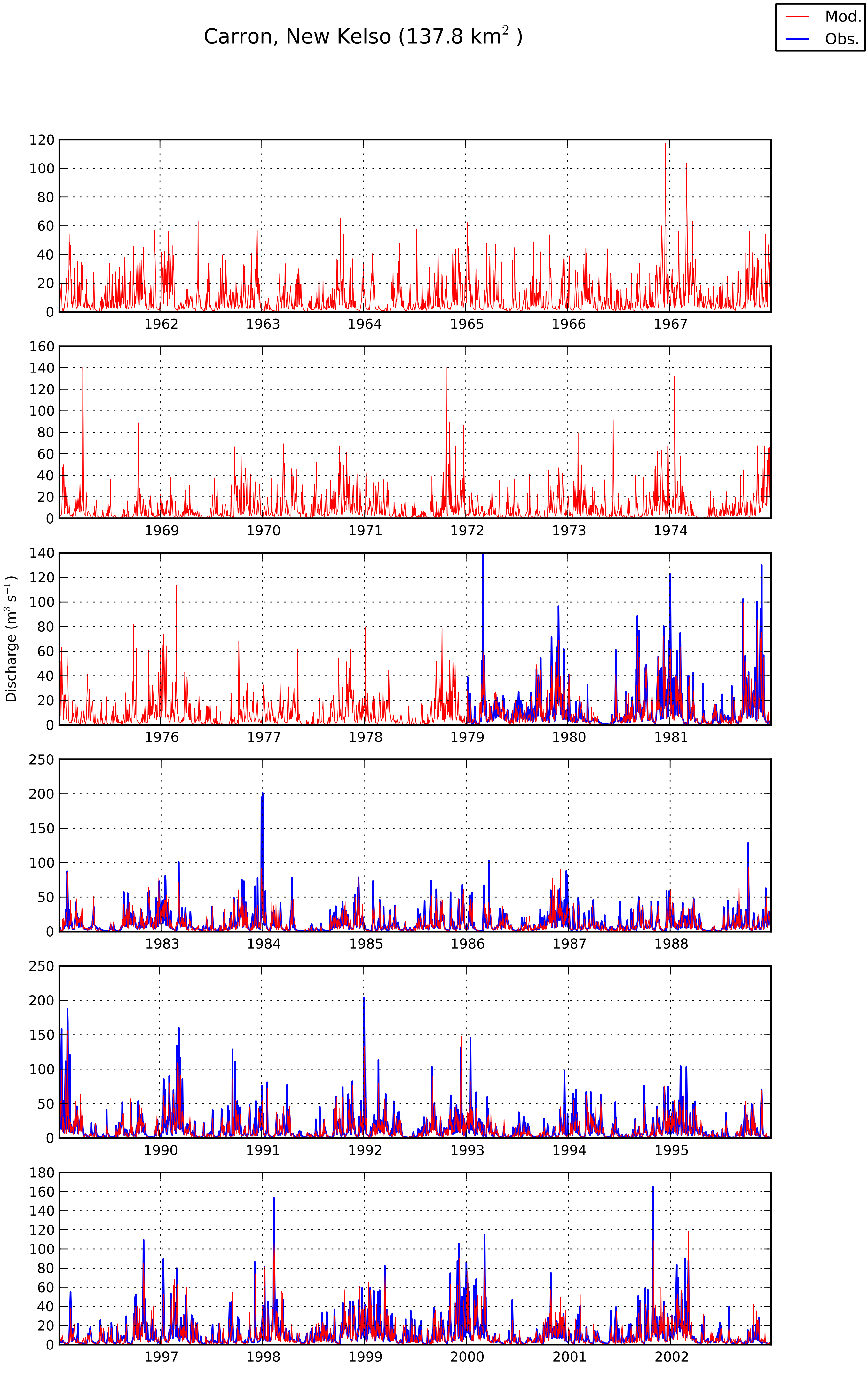

Carron, New Kelso (137.8 km^2)
Mod.
Obs.
Discharge (m^3 s^{-1})
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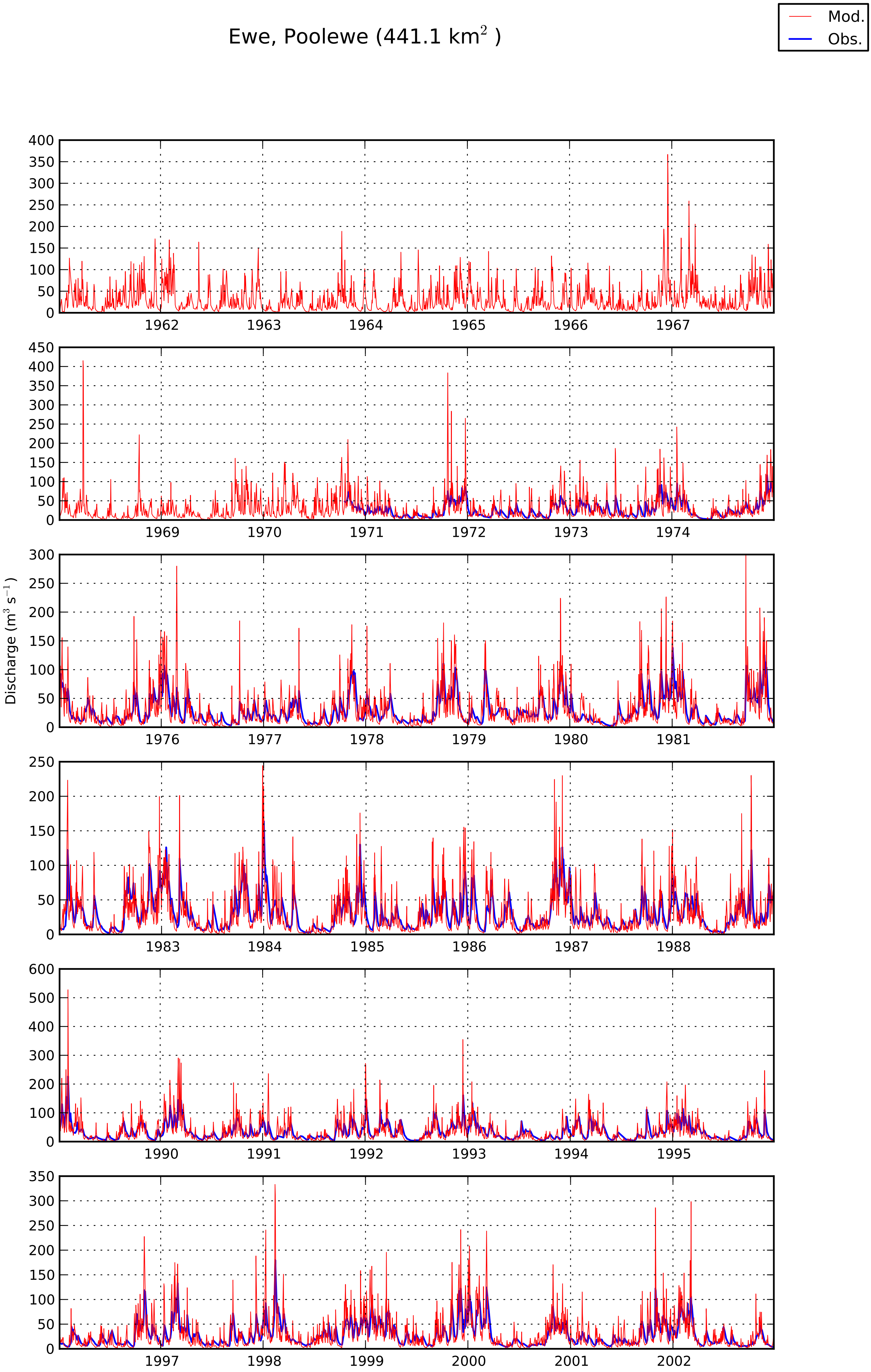
Ewe, Poolewe (441.1 km^2)
Mod.
Obs.
Discharge (m^3 s^{-1})
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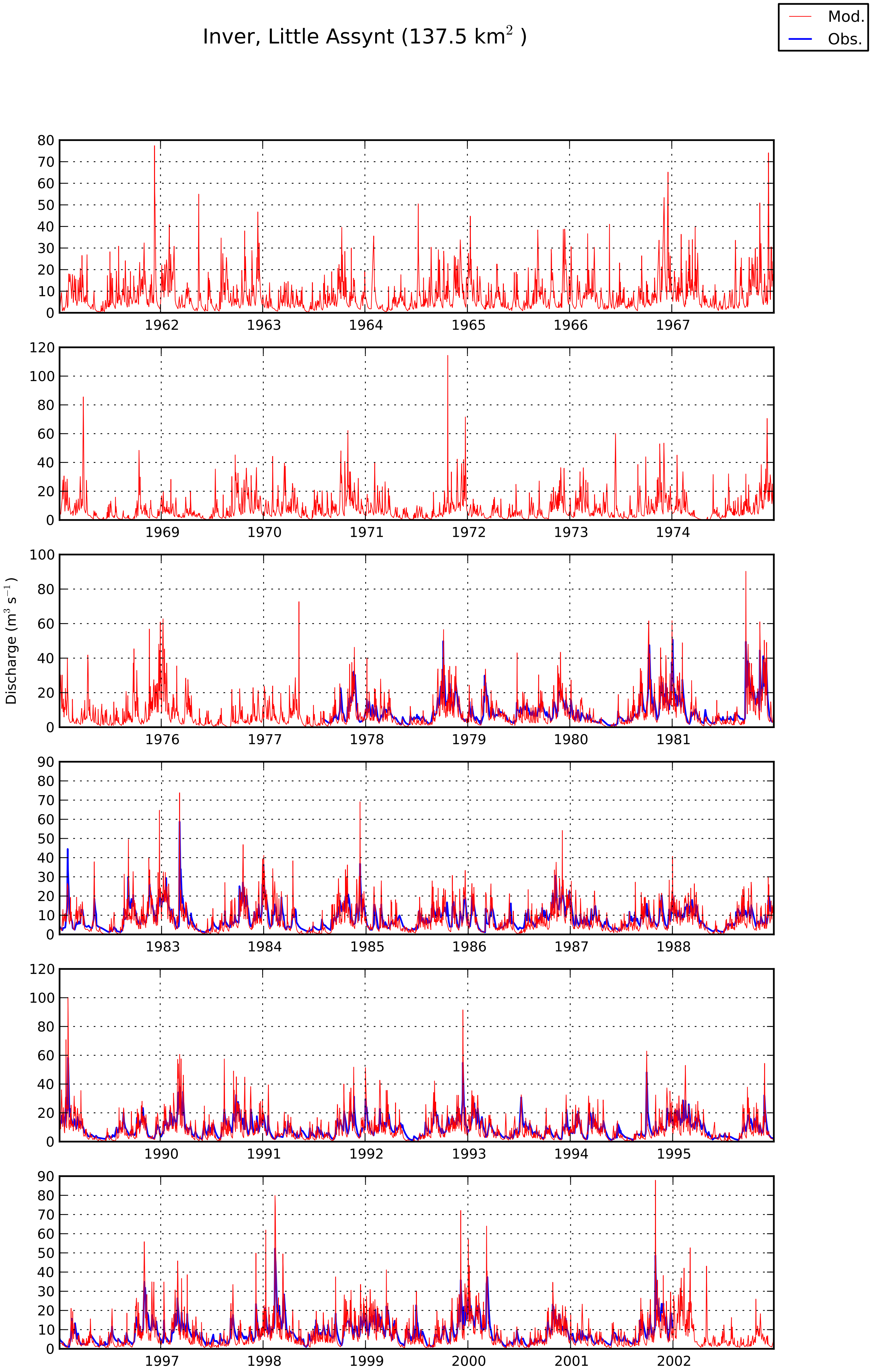
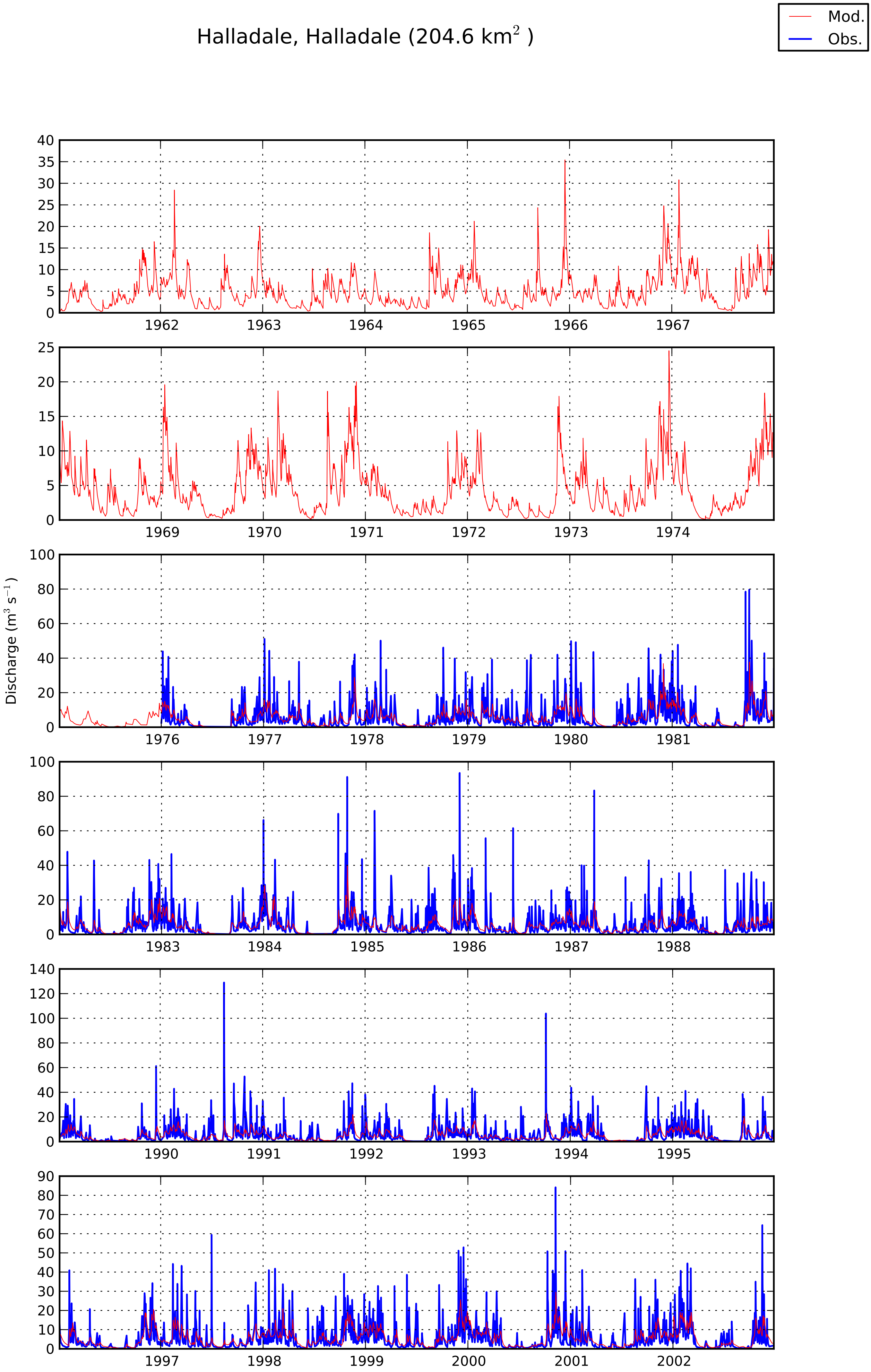
Inver, Little Assynt (137.5 km^2)




Halladale, Halladale (204.6 km^2)
Mod.
Obs.
Discharge (m^3 s^{-1})
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Appendix B
Details of Identified Hydropower Schemes

Run-of-River Sites (5% Discount Rate)

County	River	Intake Easting	Intake Northing	Power house Easting	Power house Northing	Power (MW)	Total cost (M£)	NPV (M£)	LEC (£/MWh)	Discounted Payback Period	Energy production (MWh/year)	CF	Line distance (km)	Road distance (km)	Turbine type	Gross Head (m)	Net Head (m)	Penstock Length (km)	Penstock diameter (m)	Qd (m^3s^{-1})	Qd (FDC percentile)	Q10 (m^3s^{-1})	Q50 (m^3s^{-1})	Q90 (m^3s^{-1})	Catchmnet area (km^2)
Highland	Falls of Kirkaig	211383	917701	207972	919340	10.27	15.961	28.246	40	7	38462	0.43	0.6	5.4	Francis	130	111	4.3	3	11.1	15	14.42	4.33	1.0072	137
Highland	Abhainn Cuileig	217813	876652	219388	879105	9.41	11.602	25.334	36	6	31582	0.38	0.2	3.6	Francis	159	147	3.4	2.7	7.72	15	10.24	2.42	0.5153	54
Highland	Allt a' Ghlomaich	201981	825644	200495	826710	14.93	12.752	19.712	44	7	28575	0.22	7.9	2.7	Francis	275	265	2.5	2.5	6.8	5	4.798	0.76	0.1094	20
Perth and Kinross	Allt Coire a' Mhar-fhir	299122	740592	301027	741769	5.606	10.097	19.036	39	6	25212	0.51	8.4	2.7	Francis	91.4	84.2	2.7	2.9	8.06	25	16.04	4.08	0.674	201
Highland	Lochan na Cairill	196157	891297	195973	891914	6.3	8.629	18.274	37	6	23061	0.42	9.8	0.9	Francis	56.7	51	0.7	3	15.1	20	23.85	5.4	0.9637	153
Highland	Loch Cha¹ilean Dubha	206697	867084	207340	864219	9.001	11.478	16.899	45	7	25083	0.32	3.4	3.5	Francis	200	191	3.5	2.5	5.7	10	5.898	1.4	0.3043	30
Highland	Allt Coire Eaghainn	217489	768908	215348	768408	9.228	10.852	16.143	44	7	23840	0.29	5.0	2.9	Francis	158	146	2.9	2.6	7.63	10	7.667	1.19	0.065	32
Perth and Kinross	Allt a' Chrombaidh	277059	768228	280597	765513	4.931	13.494	15.578	50	9	26250	0.61	0.8	5.2	Francis	81.4	68.3	5.0	3	8.77	35	26.48	6.23	1.3513	259
Highland	River Talladale	191698	867343	191946	870034	7.705	9.748	14.312	45	7	21271	0.32	0.2	3.1	Francis	217	212	3.1	2.5	4.4	10	4.555	1.08	0.2383	20
Highland	River E	251646	811979	249107	814499	5.167	12.091	13.203	51	9	22952	0.51	0.0	4.8	Francis	105	98.9	4.6	3	6.32	25	11.95	3.47	0.9051	115
Highland	River Glass	258114	866512	260683	866572	4.919	9.021	12.682	46	8	19261	0.45	1.0	3.1	Francis	98.4	92.1	3.1	2.8	6.47	20	10.36	2.68	0.5441	116
Perth and Kinross	Falls of Bruar The	282041	768041	282335	765977	6.815	8.642	12.509	45	7	18723	0.31	2.7	2.6	Francis	161	155	2.6	2.5	5.33	10	5.526	1.4	0.3405	67
Highland	Loch Bad na Goibhre	210119	923410	209599	923080	3.991	5.841	12.268	37	6	15533	0.44	1.4	0.7	Francis	44.8	41.5	0.7	3	11.9	20	18.7	5.29	1.1897	164
Highland	Lochan na Craoibhe-beithe	254419	824658	252056	823948	6.135	9.723	11.584	49	8	19186	0.36	3.4	3.6	Francis	171	165	3.6	2.5	4.5	10	4.693	1.46	0.3314	73
Perth and Kinross	Burn of Auchrannie	329511	751555	329118	750062	4.152	8.365	10.407	48	8	16839	0.46	6.0	2.2	Francis	57	50.7	1.8	3	10	20	16.19	4.41	0.7891	290
Highland	Loch na h-Uidhe	194274	887470	194733	889962	4.552	9.281	10.403	51	9	17820	0.45	7.1	3.2	Francis	97.9	91.2	3.2	2.7	6.05	20	9.328	2.5	0.5134	79
Highland	Abhainn Droma	221353	877367	219709	878665	5.683	7.496	9.701	48	8	15373	0.31	0.0	2.4	Francis	142	137	2.4	2.5	5.03	10	5.187	1.21	0.2634	35
Highland	Abhainn Chia-aig	218137	790483	217597	788900	6.539	8.221	8.702	52	9	15398	0.27	11.0	1.9	Francis	188	185	1.9	2.6	4.27	10	4.318	0.52	0.0743	19
Highland	Loch Kirkaldy	293521	842892	293449	842935	2.66	5.683	8.677	44	7	12653	0.54	8.2	0.3	Kaplan	17.3	16.1	0.1	3	19.4	25	33.99	11.8	2.8819	551
Highland	Allt an Ruighe	191828	824511	190612	823105	4.865	5.331	8.449	43	7	12102	0.28	6.1	2.1	Francis	263	244	2.1	1.4	2.43	10	2.471	0.39	0.0744	11
Highland	Lochain a' Mhill Dheirg	231498	932960	229877	933030	3.288	4.716	8.351	40	7	11368	0.39	4.8	9.4	Pelton	222	213	2.1	1.5	1.97	15	2.628	0.57	0.1242	14
Highland	Alness River or River Averon	263360	872868	265068	870306	4.354	12.973	8.290	63	12	20190	0.53	0.3	5.1	Francis	74	61.8	4.9	3	8.59	25	15.86	4.69	1.0151	195
Highland	Allt Lochain Buidhe	212103	881491	211663	884780	2.503	6.117	8.068	47	8	12659	0.58	6.5	4.9	Pelton	230	213	4.9	1.4	1.49	30	3.225	0.92	0.2284	25
Highland	Allt Briste	226123	935030	224983	934037	2.54	4.276	7.889	40	6	10547	0.47	6.8	6.3	Pelton	184	179	1.8	1.6	1.81	20	2.954	0.76	0.1753	22
Highland	Allt Coire an Eich	254778	804701	253561	807235	2.678	5.347	7.882	45	7	11692	0.50	7.0	5.1	Pelton	225	210	3.5	1.4	1.62	20	2.57	0.79	0.2227	25
Highland	Loch a' Mheig	243873	819298	245618	819016	2.68	3.574	7.861	36	6	9771.4	0.42	0.2	2.2	Pelton	220	211	2.2	1.4	1.61	15	2.205	0.54	0.1112	23
Highland	River Lair	198937	850207	200131	848245	3.923	4.335	7.606	41	7	10397	0.30	0.0	3.0	Pelton	329	304	2.8	1.2	1.64	10	1.665	0.22	0.0351	7
Highland	Allt a' Mhuilinn	216128	773033	213876	775654	3.736	4.299	7.543	41	7	10311	0.32	1.3	4.0	Pelton	481	444	4.0	1	1.06	10	1.062	0.14	0.0016	3
Highland	Allt Daim	217737	774430	215535	776794	3.982	4.647	7.497	43	7	10650	0.31	3.3	3.9	Pelton	475	430	3.9	1	1.17	10	1.17	0.14	0.0022	4
Highland	Rogie Falls	244654	858496	244804	857621	1.996	5.501	7.395	47	8	11489	0.66	2.9	1.4	Francis	31.3	28	1.2	3	9.08	45	32.26	8.85	1.9292	317
Highland	Lochan nan Leacann Dearga	182488	867215	181371	869295	5.221	8.755	7.274	57	10	14892	0.33	3.5	6.1	Francis	155	150	3.1	2.5	4.22	10	4.381	1.12	0.2542	21
Highland	Caochan Dir na Lair	291450	840585	291744	840695	2.82	6.912	7.270	52	9	12910	0.52	10.0	0.5	Kaplan	21.1	16.3	0.3	3	20.3	20	30.89	10.3	2.545	470
Highland	Black Water or Uisge Dubh	200156	837789	200028	836657	3.704	5.572	7.034	48	8	11294	0.35	4.2	3.7	Francis	81.1	77.4	1.3	2.5	5.82	15	7.786	1.46	0.2751	37
Highland	Allt Cam Ba n	256413	806503	253707	807019	3.289	5.534	7.023	48	8	11244	0.39	7.3	5.0	Pelton	300	271	3.7	1.2	1.54	10	1.639	0.51	0.1418	15
Highland	Allt a' Chonais	206765	848429	205509	848892	3.074	3.532	6.994	38	6	9072.3	0.34	0.8	1.8	Francis	171	164	1.6	1.6	2.27	15	2.942	0.42	0.0441	13
Highland	Water of Glencalvie	243690	888782	246689	889174	4.487	10.864	6.924	63	12	16894	0.43	12.1	3.7	Francis	91.5	82	3.7	2.7	6.64	20	10.78	2.53	0.5772	72
Highland	Ullapool River	215014	895470	212443	894494	3.591	8.367	6.918	57	10	14207	0.45	0.8	3.6	Francis	84.3	73.4	3.6	2.5	5.96	20	9.369	2.52	0.5824	79
Highland	Allt na Faithe Buidhe	194297	832050	194061	831383	2.846	5.336	6.887	48	8	10929	0.44	0.0	1.1	Francis	34.6	31.1	0.8	3	11.5	25	23.82	4.49	0.8177	131
Perth and Kinross	Black Water	314330	755313	314606	751817	3.881	10.479	6.781	62	12	16373	0.48	1.0	4.6	Francis	80.9	69	4.4	2.7	6.84	25	14.72	2.91	0.4902	180

Run-of-River Sites (5% Discount Rate)

County	River	Intake Easting	Intake Northing	Power house Easting	Power house Northing	Power (MW)	Total cost (M£)	NPV (M£)	LEC (£/MWh)	Discounted Payback Period	Energy production (MWh/year)	CF	Line distance (km)	Road distance (km)	Turbine type	Gross Head (m)	Net Head (m)	Penstock Length (km)	Penstock diameter (m)	Qd (m^3s^{-1})	Qd (FDC percentile)	Q10 (m^3s^{-1})	Q50 (m^3s^{-1})	Q90 (m^3s^{-1})	Catchmnet area (km^2)
Stirling	Falls of Leny	259176	708718	260851	708222	2.981	7.820	6.720	57	10	13471	0.52	0.8	2.1	Francis	43.5	35.9	2.1	3	10.3	35	34.4	5.15	0.626	196
Highland	Allt Airdeasaidh	204787	888224	205304	889740	3.921	5.421	6.712	49	8	10888	0.32	15.0	1.9	Pelton	306	286	1.9	1.2	1.74	10	1.779	0.32	0.0581	11
Argyll and Bute	Eas a' Ghaill	222713	727047	220081	727297	6.501	9.934	6.561	62	12	15621	0.27	4.7	3.2	Francis	119	105	3.0	2.5	7.47	10	7.533	0.84	0.1038	32
Argyll and Bute	Allt Hallater	214126	738467	215426	737477	3.659	4.413	6.539	45	7	9675.3	0.30	6.8	1.8	Pelton	276	256	1.8	1.2	1.82	10	1.839	0.23	0.022	7
Highland	Abhainn na Fa¹irneis	197971	870385	195947	870680	3.704	5.360	6.365	50	8	10560	0.33	7.7	3.3	Pelton	263	241	2.6	1.3	1.96	10	2.001	0.36	0.059	9
Argyll and Bute	Eagle's Fall	222706	714223	221617	714787	4.637	3.888	6.338	42	7	8959.2	0.22	3.5	1.6	Pelton	370	349	1.4	1.1	1.69	5	1.209	0.14	0.0357	5
Highland	Allt Ba n an La¬-ruighe	197883	826084	198302	827114	2.775	3.259	6.288	39	6	8246.8	0.34	5.9	1.8	Pelton	337	321	1.6	1	1.09	10	1.125	0.26	0.055	6
Perth and Kinross	Allt na Moine Ba ine	288139	770202	287620	766381	4.551	12.818	6.242	68	14	18477	0.46	5.1	4.7	Francis	80.2	67.3	4.7	2.9	8.22	25	19.09	3.35	0.778	198
Highland	River Grudie	195852	865320	196387	867081	3.517	5.750	6.168	52	9	10830	0.35	0.6	2.7	Francis	108	105	2.1	2.5	4.06	15	5.347	1.02	0.1634	22
Highland	Allt Grannda	202385	817090	200624	817401	3.757	6.154	6.065	54	9	11187	0.34	15.9	3.9	Francis	222	215	2.2	1.6	2.13	15	2.744	0.4	0.0118	9
Highland	Allt Coire na Creiche	186486	761764	185282	760779	3.045	3.427	6.008	41	7	8215.5	0.31	0.2	1.9	Pelton	255	238	1.9	1.2	1.63	10	1.647	0.23	0.0338	5
Highland	River E	254637	813629	251994	816472	2.16	4.242	5.847	46	8	8969.1	0.47	0.2	5.0	Pelton	301	253	5.0	1	1.08	15	1.396	0.45	0.1191	16
Highland	Tollie Bay	186970	878852	186882	878930	1.642	4.406	5.829	47	8	9131.1	0.63	0.8	0.3	Kaplan	11.3	9.62	0.1	3	20.3	40	66.8	16.3	3.3932	430
Perth and Kinross	Falls of Moness	285065	747188	285540	749129	2.349	3.374	5.719	41	7	7940.5	0.39	1.6	2.3	Pelton	202	181	2.3	1.2	1.65	10	1.685	0.47	0.0794	25
Stirling	Allt Dha¹in Croisg	253754	738017	252852	736302	4.039	4.280	5.718	47	8	8913.2	0.25	0.0	2.5	Francis	255	232	2.3	1.3	2.11	10	2.132	0.19	0.0322	9
Perth and Kinross	Allt Da -ghob	271211	747234	272674	747552	2.086	6.436	5.625	56	10	11158	0.61	0.9	1.9	Francis	34.7	29.7	1.9	3	8.89	45	49.79	7.53	1.1524	310
Highland	Loch a' Bhaid-bheithe	250226	892607	251482	892564	2.058	6.414	5.587	56	10	11106	0.62	5.9	1.5	Francis	32.5	28.1	1.5	3	9.3	40	29.61	7.65	1.6294	247
Argyll and Bute	Allt Cnoc an Tighe	225146	733949	223557	777977	2.139	5.977	5.397	56	10	10493	0.56	1.5	1.4	Francis	30.5	25.7	1.2	3	10.7	40	48.28	7.23	1.2129	234
Perth and Kinross	Allt an Stalcair	269497	771545	272847	770023	3.359	9.438	5.269	65	13	14113	0.48	4.8	4.1	Francis	80.8	68.1	4.1	2.5	6.01	25	13.68	2.65	0.5667	113
Highland	An Garbh-allt	178757	851756	178759	854925	1.9	4.549	5.136	51	9	8762.5	0.53	4.3	4.2	Pelton	199	171	4.2	1.2	1.41	25	2.762	0.66	0.136	17
Highland	Loch Mar	299061	824803	300185	824330	2.142	5.650	5.050	56	10	9879	0.53	1.4	1.8	Francis	40.2	36.8	1.6	2.9	7.28	25	12.56	4.31	0.8808	271
Stirling	Allt Criche	232890	718194	232121	718584	3.392	4.128	5.013	49	8	8217.6	0.28	12.6	1.3	Pelton	280	271	1.1	1.2	1.59	10	1.604	0.14	0.0217	7
Highland	Allt Ma iri	219528	783103	219426	783124	1.512	5.269	5.000	55	10	9433.2	0.71	9.6	1.5	Kaplan	10.6	9.15	0.1	3	19.7	50	102.6	22.1	4.3817	824
Highland	Achness Waterfall	246723	903397	246743	902747	1.954	5.754	4.994	56	10	9949.3	0.58	10.9	1.1	Francis	28.9	26.5	0.8	3	9.44	35	22.81	7.14	1.7076	179
Highland	Allt a' Choire Dhuibh	202056	836104	200627	836254	3.264	5.821	4.961	57	10	9996.9	0.35	4.8	5.4	Francis	109	107	1.9	2.5	3.7	15	4.963	0.93	0.1735	35
Highland	Allt Guibhais	206321	863031	204961	862316	2.177	5.735	4.925	57	10	9877.1	0.52	0.4	1.7	Francis	40.1	36.2	1.7	2.9	7.5	30	17.7	4.26	0.9459	112
Argyll and Bute	Allt nam Muc	204346	707107	206225	704807	1.67	3.807	4.885	48	8	7775.4	0.53	0.5	4.0	Pelton	182	167	4.0	1.3	1.26	30	4.041	0.58	0.1406	21
East Ayrshire	Burnock Water	250514	621568	250323	621819	1.625	3.097	4.873	43	7	7004.4	0.49	0.3	0.5	Francis	29.9	29.1	0.3	2.8	7.1	25	12	3.81	0.5721	204
Angus	Falls of Damff	338510	778898	338825	780271	3.675	5.720	4.780	57	10	9751	0.30	17.3	2.3	Pelton	250	235	1.7	1.3	2	10	2.036	0.37	0.0665	27
Highland	Shin Falls	257634	899571	257662	899389	1.282	3.964	4.741	49	8	7835	0.70	0.6	0.2	Kaplan	11.2	9.25	0.2	3	16.5	45	51.4	16.3	3.5224	574
Perth and Kinross	Allt a' Mha gain	292649	765152	291180	762873	1.859	3.654	4.718	48	8	7485.6	0.46	2.1	3.1	Pelton	168	151	3.1	1.3	1.56	20	2.786	0.55	0.0962	36
Stirling	Dubh Eas	230120	720575	231888	719887	5.316	8.235	4.593	65	13	12311	0.26	11.2	2.4	Francis	179	177	2.4	2.5	3.65	10	3.706	0.46	0.1013	21
Highland	Allt a' Chraois	244649	939543	245179	942511	1.753	4.898	4.579	55	10	8717.1	0.57	12.3	3.5	Pelton	170	154	3.5	1.3	1.44	30	3.257	0.82	0.1713	19
Argyll and Bute	Garbh-allt Mar	221476	713017	220457	713806	2.299	2.268	4.479	38	6	5815.7	0.29	2.0	1.5	Pelton	390	365	1.5	0.8	0.79	10	0.804	0.1	0.0265	4
Highland	Allt a' Choire Ghlais	226161	796553	227914	795793	3.222	4.448	4.423	53	9	8115.9	0.29	5.2	2.6	Pelton	269	247	2.4	1.2	1.66	10	1.672	0.17	0.0231	9
Moray	Allt na Ha	316987	828709	318290	830910	2.245	8.965	4.382	68	14	12936	0.66	2.8	3.8	Francis	42.4	35.3	3.3	3	7.96	40	22.53	7.1	1.6888	361
Aberdeenshire	Loch Kinord	345940	798215	346127	798225	1.169	3.986	4.370	51	9	7579	0.74	1.2	0.2	Kaplan	10.2	8.23	0.2	3	17	50	69.81	19.4	4.3851	1030
Highland	Allt Gartain	217581	751067	216911	750952	2.709	6.031	4.346	60	11	9757.5	0.41	7.8	1.0	Francis	36.6	33.7	0.8	3	10.1	25	21.73	3.06	0.468	97
Highland	River Coiltie	247163	827048	250811	828811	1.426	3.825	4.338	51	9	7382	0.59	0.3	4.9	Pelton	177	155	4.9	1.2	1.16	30	2.835	0.7	0.1349	34
Argyll and Bute	Eas an Amair	200794	713126	199616	713445	1.746	2.399	4.306	40	6	5826	0.38	0.2	1.6	Pelton	174	167	1.6	1.3	1.32	15	1.843	0.38	0.0875	9

Run-of-River Sites (5% Discount Rate)

County	River	Intake Easting	Intake Northing	Power house Easting	Power house Northing	Power (MW)	Total cost (M£)	NPV (M£)	LEC (£/MWh)	Discounted Payback Period	Energy production (MWh/year)	CF	Line distance (km)	Road distance (km)	Turbine type	Gross Head (m)	Net Head (m)	Penstock Length (km)	Penstock diameter (m)	Qd (m^3s^{-1})	Qd (FDC percentile)	Q10 (m^3s^{-1})	Q50 (m^3s^{-1})	Q90 (m^3s^{-1})	Catchmnet area (km^2)
Perth and Kinross	Falls of Tarf	298172	779691	298340	778783	3.772	7.368	4.290	64	13	11151	0.34	19.5	4.6	Francis	73	68.7	1.1	2.5	6.69	15	9.585	1.8	0.4581	59
Argyll and Bute	Donich Water	221366	701853	220229	701927	2.003	2.597	4.225	42	7	5977.3	0.34	0.5	1.4	Pelton	150	140	1.4	1.3	1.82	15	2.393	0.25	0.0146	7
Highland	Allt Garaidh Ghualaich	215762	798809	217031	800517	1.411	2.951	4.192	45	8	6332.8	0.51	0.8	2.5	Pelton	131	118	2.5	1.3	1.51	25	3.22	0.69	0.1501	17
Argyll and Bute	Allt Beochlich	202390	715166	200573	715376	2.017	2.903	4.163	45	8	6260.5	0.35	0.2	2.3	Pelton	223	211	2.3	1.2	1.21	15	1.66	0.26	0.0606	9
Highland	Allt Fionn Ghlinne	221931	751927	219606	751127	3.693	8.701	4.152	68	14	12479	0.39	6.2	2.8	Francis	68.9	59.7	2.8	2.7	7.55	20	13.28	2	0.3831	64
Highland	Black Water	279357	913647	280245	911569	2.273	8.323	4.149	67	14	12070	0.61	11.9	2.9	Francis	49.3	45.2	2.7	2.9	6.22	35	13.2	4.72	0.9552	201
Stirling	Allt Fionn Ghlinne	232211	722394	233211	720565	2.838	5.044	4.112	58	11	8521	0.34	10.7	2.7	Pelton	219	208	2.5	1.4	1.74	15	2.347	0.27	0.0473	10
Highland	Allt a' Choire Dhuibh Mhair	194706	859006	196077	857253	2.488	3.444	4.086	50	8	6782.8	0.31	8.8	2.9	Pelton	463	430	2.5	0.8	0.72	10	0.73	0.11	0.0082	2
Highland	River Einig	234679	898049	235960	898633	2.487	8.163	3.994	68	14	11782	0.54	19.9	2.7	Francis	41.3	37.7	1.6	3	8.21	30	17.91	5.13	1.1923	153
Highland	Allt Coire an t-Sneachda	219519	825898	221231	824120	2.021	4.487	3.994	56	10	7833.1	0.44	7.1	3.4	Pelton	180	168	3.2	1.4	1.53	25	3.593	0.45	0.0807	18
Highland	Loch a' Mheallain Odhair	208398	866743	207645	864165	1.544	3.835	3.977	53	9	7119.9	0.53	3.6	4.9	Pelton	169	147	3.8	1.2	1.33	25	2.684	0.63	0.1361	16
Highland	Loch Bra igh Horrisdale	179533	870801	178892	871431	2.281	4.512	3.962	56	10	7835.9	0.39	4.8	2.6	Francis	63.1	61.2	1.1	2.5	4.57	15	5.868	1.69	0.387	36
Highland	Abhainn Coire Mhic Nabuil	187794	858682	186987	857187	4.433	7.886	3.913	67	14	11423	0.29	13.2	2.0	Francis	128	124	2.0	2.5	4.32	10	4.397	0.78	0.1235	19
Aberdeenshire	Burn of Glendui	342443	796627	342638	796647	1.13	4.149	3.799	55	10	7323.6	0.74	2.8	0.5	Kaplan	10.1	8.1	0.2	3	16.7	50	68.7	19	4.3068	1008
East Ayrshire	Cessnock Water	250955	625400	250312	625357	1.539	3.620	3.755	53	9	6722.4	0.50	0.6	1.2	Francis	32	30.2	0.8	2.7	6.47	25	11.7	3.5	0.5308	182
Argyll and Bute	Allt Arnan	230697	716730	231465	716684	2.693	3.520	3.721	52	9	6589	0.28	14.1	0.9	Pelton	208	202	0.9	1.3	1.69	10	1.712	0.16	0.03	6
Argyll and Bute	Loch Fyne	220024	709617	217976	710763	3.709	7.361	3.692	67	13	10691	0.33	0.3	3.1	Francis	97.3	90.8	3.1	2.5	4.96	15	6.429	0.76	0.0315	24
Argyll and Bute	Cladich River	211013	720760	209732	722503	1.334	2.878	3.675	48	8	5864.4	0.50	0.2	3.2	Pelton	150	134	3.0	1.2	1.26	25	3.056	0.53	0.1241	18
Argyll and Bute	River Shira	214053	713064	212946	713387	1.885	2.257	3.671	42	7	5195	0.31	0.2	1.4	Pelton	190	177	1.4	1.1	1.35	10	1.383	0.28	0.0657	6
Highland	Allt Poll Doire	171147	752370	170194	750667	2.726	5.426	3.632	62	12	8568.4	0.36	0.0	2.4	Francis	90.8	88.2	2.2	2.5	3.76	15	4.957	1.04	0.1963	28
Highland	Allt Coire a' Mhusgain	215784	763332	216574	761987	2.455	3.257	3.618	51	9	6229.2	0.29	0.5	2.1	Pelton	221	210	2.1	1.3	1.48	10	1.487	0.15	0.0066	6
Stirling	Allt nan Sliseag	245068	729984	245311	728364	3.123	4.504	3.615	58	11	7565.3	0.28	9.3	2.0	Pelton	260	243	2.0	1.2	1.64	10	1.663	0.17	0.0406	6
Highland	Allt na Fea rna	236788	808803	236900	808979	0.992	3.452	3.613	52	9	6434.8	0.74	0.3	0.4	Kaplan	10.1	8.5	0.2	3	14	55	84.08	18.8	3.3723	486
Highland	Allt Coire na Ba	219120	763688	218546	762323	2.351	2.892	3.612	48	8	5832.5	0.28	0.5	1.7	Pelton	225	218	1.7	1.3	1.36	10	1.365	0.11	0.0005	4
Argyll and Bute	Allt Arnan	230538	718894	231675	718410	2.974	4.284	3.565	57	10	7292	0.28	12.7	1.4	Pelton	218	211	1.4	1.4	1.8	10	1.81	0.16	0.0259	6
Argyll and Bute	Abhain a' Bhealaich	197205	705639	195665	707650	2.098	3.705	3.531	54	10	6644.5	0.36	0.2	3.0	Pelton	176	163	3.0	1.4	1.63	15	2.254	0.37	0.0931	13
Highland	River Douchary	225466	891467	225509	893086	1.328	3.767	3.531	55	10	6710.4	0.58	9.4	4.2	Pelton	123	112	2.3	1.3	1.51	30	3.693	0.92	0.2114	28
D&G	Cargen Pow	296845	576109	297067	575897	1.071	4.262	3.529	57	10	7241.2	0.77	0.2	0.3	Kaplan	10.6	7.21	0.3	3	17.9	55	102.1	22.3	3.2697	1114
Highland	Abhainn Loch na h-Oidhche	188248	867242	187173	869320	2.003	4.222	3.514	57	10	7187.3	0.41	3.0	6.7	Pelton	196	169	3.6	1.2	1.51	15	1.968	0.43	0.0883	9
Aberdeenshire	Linn of Muick (Waterfall)	333081	789385	334971	792785	3.253	9.470	3.488	72	15	12804	0.45	5.5	4.7	Francis	110	105	4.7	2.5	3.77	20	6.398	1.61	0.366	79
Highland	Allt Coire Mhuillidh	227413	840813	228106	838431	2.63	3.693	3.480	55	10	6593	0.29	0.0	2.9	Pelton	261	229	2.9	1.1	1.46	10	1.465	0.13	0.0135	5
Highland	Alltan Odhar	195101	847084	195401	845706	1.504	2.650	3.425	48	8	5431.1	0.41	0.8	2.2	Pelton	113	105	1.6	1.4	1.83	20	3.001	0.46	0.0635	13
Highland	Allt Coire Misirich	253325	867346	256156	868056	1.556	3.590	3.417	54	10	6434.2	0.47	3.5	3.7	Pelton	169	149	3.4	1.2	1.33	20	2.336	0.51	0.1115	25
Stirling	River Dochart	249293	730367	250989	729522	3.018	4.292	3.406	58	11	7180.6	0.27	4.6	2.4	Pelton	257	235	2.4	1.2	1.63	10	1.649	0.12	0.0249	7
Highland	River Beauly	249809	843978	249976	843783	1.112	4.736	3.339	61	11	7607.2	0.78	0.8	0.5	Kaplan	10.5	6.37	0.3	3	21.2	55	134.5	28.8	5.3428	916
Highland	Allt Gleann a' Mhadaidh	221357	885810	218854	885430	1.221	2.491	3.330	47	8	5189	0.49	0.0	3.1	Pelton	181	168	3.1	1.1	0.91	20	1.479	0.4	0.0998	7
Argyll and Bute	Eas na Gea rr	199227	737178	198826	735490	1.987	3.044	3.317	51	9	5772.6	0.33	0.3	2.3	Pelton	168	154	2.3	1.3	1.64	15	2.131	0.18	0.0188	13
Argyll and Bute	River Goil	217529	700097	218956	700327	2.305	3.049	3.317	51	9	5778.8	0.29	0.3	1.8	Pelton	167	158	1.8	1.4	1.86	10	1.871	0.17	0.0153	8
Highland	River Farrar	232384	841193	231996	839879	1.607	1.774	3.315	39	6	4407	0.31	0.2	1.6	Pelton	319	301	1.6	0.8	0.67	10	0.685	0.14	0.0311	4
Stirling	Falls of Dochart	256980	732343	257387	732740	1.423	4.097	3.301	58	11	6892.2	0.55	0.4	0.6	Francis	20.3	18	0.6	3	10.6	40	44.16	7.6	1.3215	235

Run-of-River Sites (5% Discount Rate)

County	River	Intake Easting	Intake Northing	Power house Easting	Power house Northing	Power (MW)	Total cost (M£)	NPV (M£)	LEC (£/MWh)	Discounted Payback Period	Energy production (MWh/year)	CF	Line distance (km)	Road distance (km)	Turbine type	Gross Head (m)	Net Head (m)	Penstock Length (km)	Penstock diameter (m)	Qd (m^3s^{-1})	Qd (FDC percentile)	Q10 (m^3s^{-1})	Q50 (m^3s^{-1})	Q90 (m^3s^{-1})	Catchmnet area (km^2)
Highland	Allt Gleann Chaorachain	210361	885348	211142	885882	1.861	3.182	3.283	53	9	5895.7	0.36	7.6	1.3	Pelton	152	145	1.3	1.3	1.63	15	2.149	0.34	0.0519	10
Highland	Allt na Claise Brice	171615	747109	170766	747248	0.97	2.005	3.261	42	7	4614.4	0.54	1.3	1.0	Francis	72.2	69	1.0	1.5	1.73	30	3.785	1.04	0.2104	29
Highland	Allt Chomhraig	278648	797770	278622	800043	2.252	6.746	3.258	68	14	9703.8	0.49	1.0	3.1	Francis	58.2	50.9	2.9	2.5	5.44	25	10.92	2.66	0.5786	129
Highland	Lochan Lice	248741	880115	250236	878476	3.019	7.834	3.233	70	15	10853	0.41	10.1	3.1	Francis	107	104	3.1	2.5	3.54	15	4.609	1.41	0.3589	44
Stirling	Waltersmuir Resr	277901	702076	278211	700830	1.706	5.450	3.211	64	13	8277.2	0.55	1.0	2.0	Francis	39.7	35.5	2.0	2.7	6.02	30	11.96	3.73	0.6144	180
Highland	Allt Choire a' Chait	210679	812487	210709	811286	2.152	2.947	3.196	52	9	5577.6	0.30	8.4	1.4	Pelton	341	328	1.4	0.9	0.82	10	0.835	0.11	0.0175	3
South Lanarkshire	River Clyde	281628	646508	282435	647049	1.457	3.228	3.159	54	10	5850.8	0.46	0.5	1.1	Francis	56.2	55.2	1.1	2.5	3.25	20	4.914	1.46	0.1969	87
Argyll and Bute	Allt Lairig lanachain	212243	731020	212964	729748	1.968	2.602	3.153	49	8	5173.9	0.30	0.2	1.8	Pelton	171	163	1.6	1.3	1.53	10	1.537	0.18	0.0024	3
Highland	Lochan Giubhais	198566	887168	198403	888036	2.108	6.270	3.132	67	14	9097.6	0.49	10.2	5.3	Francis	31.2	28.1	1.0	3	9.55	30	22.56	4.91	0.8654	137
Highland	River Loxford	225573	946139	225510	946213	1.38	2.773	3.080	51	9	5303.2	0.44	0.0	0.5	Francis	21.6	21.4	0.1	3	8.49	25	16.3	3.96	0.7831	113
Highland	River Farrar	235232	841584	237181	839806	1.524	2.425	2.982	49	8	4855	0.36	0.2	3.3	Pelton	318	280	3.3	0.8	0.68	15	0.977	0.15	0.0294	8
Highland	Allt Choimhlidh	224219	775632	224706	732899	3.04	5.293	2.979	65	13	7932.2	0.30	11.4	2.9	Pelton	251	225	2.7	1.2	1.72	10	1.729	0.19	0.0134	7
Highland	Allt a Gheallaidh	317633	836410	317560	836494	1.045	3.305	2.969	56	10	5791	0.63	2.4	0.1	Kaplan	10.4	9.73	0.1	3	12.8	35	30.55	10.2	2.3567	544
Perth and Kinross	Falls of Keltney	276629	751296	277419	748962	1.454	2.940	2.957	53	9	5389.7	0.42	0.5	2.9	Pelton	150	131	2.9	1.2	1.4	20	2.681	0.37	0.0485	32
Highland	River Shiel	199359	813234	197617	813634	3.542	7.530	2.956	71	15	10319	0.33	15.1	2.3	Francis	98.6	94.9	2.1	2.5	4.53	15	5.91	0.82	0.038	20
Argyll and Bute	Leth Allt	205796	690273	203763	690498	1.961	3.288	2.946	56	10	5754.5	0.34	0.7	2.5	Pelton	183	175	2.5	1.4	1.42	15	1.946	0.21	0.0449	9
Highland	Allt a' Charnaich	234789	802958	234092	803249	1.507	2.182	2.945	47	8	4566	0.35	0.5	0.9	Francis	93.6	89.4	0.9	1.5	2.06	15	2.849	0.54	0.0958	24
Highland	Allt Coire Shaile	212906	842391	212686	841388	2.308	3.667	2.924	58	11	6145	0.30	8.9	8.4	Pelton	193	183	1.2	1.2	1.61	10	1.626	0.23	0.0312	6
Highland	Loch Fa¨ith an Leathaid	217725	922818	215195	924398	1.584	3.828	2.891	59	11	6293.1	0.45	6.2	3.8	Pelton	199	176	3.4	1.1	1.13	15	1.495	0.44	0.1062	13
Highland	Allt Eiteachan	260784	886524	262962	887725	1.234	2.748	2.891	52	9	5133.2	0.47	0.0	2.9	Pelton	141	126	2.9	1.2	1.24	15	1.559	0.52	0.1079	23
Highland	Dog Falls	237657	789357	236718	791903	2.44	5.434	2.867	66	13	7999.9	0.37	11.4	6.4	Pelton	217	198	3.4	1.3	1.56	15	2.17	0.39	0.0879	14
Highland	Allt Arcabhi	205538	793417	205348	792392	2.1	3.376	2.843	57	10	5771.6	0.31	10.9	1.2	Pelton	242	229	1.2	1	1.16	10	1.182	0.22	0.044	5
Highland	Allt Ba n	196229	806935	195312	806505	2.623	4.339	2.786	63	12	6763	0.29	13.5	1.2	Pelton	183	173	1.2	1.3	1.94	10	1.943	0.21	0.0063	7
Highland	Abhainn Dheabhag	226740	822524	227636	823850	1.107	3.121	2.763	56	10	5437.6	0.56	7.8	3.0	Pelton	102	96.1	1.9	1.4	1.46	30	3.864	0.82	0.1544	30
Highland	Craig River	178791	863593	176943	863885	1.471	4.043	2.740	62	12	6409.9	0.50	10.7	6.5	Pelton	140	129	2.3	1.3	1.44	20	2.236	0.66	0.1539	17
Stirling	Allt Criche	233826	720829	232191	720025	3.646	7.430	2.724	72	15	10036	0.31	11.0	2.1	Francis	81.6	75.4	2.1	2.5	5.88	15	7.856	0.79	0.0875	37
Highland	Allt Chaiseagall	257353	907072	257577	906888	0.873	3.290	2.703	58	11	5573.9	0.73	0.2	0.3	Kaplan	10	8.42	0.3	3	12.5	50	45.34	14.3	3.1002	484
Highland	Allt a' Choire Bhuidhe	257923	818038	255988	819808	1.143	2.424	2.702	51	9	4643.3	0.46	1.9	3.4	Pelton	281	254	3.4	0.8	0.56	15	0.734	0.23	0.0592	8
Highland	Lochan An Tuirc	243162	779899	243812	782108	2.444	8.265	2.701	74	16	10915	0.51	9.0	2.6	Francis	51.4	47.8	2.6	3	6.3	30	16.34	3.28	0.6182	112
Perth and Kinross	Allt a' Chobhair	262519	745299	262576	746999	2.965	4.574	2.699	64	13	6949.1	0.27	8.6	2.0	Pelton	211	200	2.0	1.4	1.89	10	1.895	0.11	0.0057	10
Highland	Loch Belivat	294588	844795	294824	845155	1.109	4.488	2.679	64	12	6842	0.70	6.6	0.8	Kaplan	13.6	11.4	0.5	3	11.6	45	34.46	11.9	2.9284	564
Highland	Allt a' Bhuiridh	177255	780227	177899	781746	1.803	2.546	2.675	52	9	4753.7	0.30	0.9	3.1	Pelton	211	198	1.9	1.1	1.15	10	1.159	0.14	0.0121	5
Highland	Dubh Lighe	194450	781673	193320	780382	3.296	5.562	2.670	68	14	7989.1	0.28	0.2	2.1	Francis	98.9	95.9	2.1	2.5	4.17	10	4.187	0.52	0.0209	14
Highland	Lochan Dubha Ca¹l a' Mhill	188498	853148	188707	854387	2.037	3.210	2.662	57	10	5457.4	0.31	6.8	1.6	Pelton	217	210	1.6	1.2	1.23	10	1.246	0.19	0.0289	6
Highland	Caochan Dir na Lair	292224	840645	292596	840517	1.284	5.179	2.646	67	13	7559.2	0.67	10.2	1.8	Kaplan	14.8	12.2	0.5	3	12.5	40	32.94	11.2	2.7366	517
South Lanarkshire	Stonebyres Falls	289569	645630	288187	645602	1.557	4.234	2.637	63	12	6537.2	0.48	1.2	2.3	Francis	59.8	58.2	1.8	2.5	3.29	20	4.694	1.62	0.2367	108
Stirling	Allt Gleann a' Chlachain	236546	731000	235308	728852	1.785	3.614	2.613	60	11	5853.5	0.37	3.6	3.0	Pelton	178	166	3.0	1.3	1.36	20	2.348	0.2	0.018	8
Renfrewshire	River Calder	233206	661454	234877	659570	1.012	3.078	2.596	57	10	5264.4	0.59	7.1	3.4	Pelton	124	109	3.4	1.2	1.18	30	3.612	0.72	0.1595	23
South Ayrshire	Water of Fail	239072	623508	238813	623211	1	3.725	2.589	61	12	5954.7	0.68	1.1	0.7	Kaplan	12.6	10.5	0.5	3	11.4	45	33.84	10.6	1.5727	571
Perth and Kinross	Allt an Fhionn	266648	725930	267008	724615	1.874	2.548	2.587	53	9	4689.6	0.29	2.0	1.5	Pelton	192	178	1.5	1.1	1.33	10	1.348	0.19	0.0298	12

Run-of-River Sites (5% Discount Rate)

County	River	Intake Easting	Intake Northing	Power house Easting	Power house Northing	Power (MW)	Total cost (M£)	NPV (M£)	LEC (£/MWh)	Discounted Payback Period	Energy production (MWh/year)	CF	Line distance (km)	Road distance (km)	Turbine type	Gross Head (m)	Net Head (m)	Penstock Length (km)	Penstock diameter (m)	Qd (m^3s^{-1})	Qd (FDC percentile)	Q10 (m^3s^{-1})	Q50 (m^3s^{-1})	Q90 (m^3s^{-1})	Catchmnet area (km^2)
Na h-Eileanan an Iar	Lochan Tana	138025	915864	138177	915233	1.562	4.720	2.582	66	13	7018.1	0.51	8.2	1.5	Francis	59.1	57.7	1.5	2.5	3.33	25	5.499	1.89	0.3992	80
Highland	River Taodail	195862	841724	194433	842135	0.983	2.056	2.567	48	8	4144.9	0.48	0.2	2.1	Pelton	100	92.7	1.9	1.3	1.34	25	2.966	0.5	0.0892	14
Highland	Garbh Allt	237597	931485	238346	931965	1.385	1.916	2.559	47	8	3989.3	0.33	1.6	4.0	Pelton	170	164	1.0	1.1	1.06	10	1.092	0.23	0.0516	7
Highland	Abhainn an Lain	233142	941641	230971	942160	1.232	3.122	2.537	58	11	5268.3	0.49	1.4	3.3	Pelton	142	124	3.3	1.2	1.25	25	2.539	0.48	0.0816	13
Highland	Loch na Sa¹iteig	189419	848338	187341	846750	1.556	3.124	2.537	58	11	5270	0.39	0.5	4.1	Pelton	152	129	2.9	1.2	1.53	15	2.002	0.34	0.0618	10
Highland	Mathair a' Gharbh Uilt	227743	950379	226892	949850	0.948	2.239	2.530	51	9	4313.9	0.52	2.1	3.9	Francis	80.6	75.8	1.3	1.4	1.54	30	3.619	0.82	0.1477	24
Highland	Allt Uchd Rodha	225660	839607	225629	838333	1.616	2.134	2.526	50	8	4199	0.30	0.2	1.6	Pelton	192	173	1.6	1	1.18	10	1.198	0.17	0.0325	7
Argyll and Bute	Allt Easach	206316	741416	207016	739321	1.836	4.030	2.523	63	12	6233.2	0.39	8.4	3.2	Pelton	166	152	2.6	1.3	1.53	20	2.595	0.29	0.0425	8
Perth and Kinross	Loch Farleyer	280970	750462	281599	749410	0.957	1.406	2.482	41	7	3383.2	0.40	0.6	1.4	Pelton	209	195	1.4	0.8	0.61	15	0.885	0.18	0.0225	14
Highland	Allt Duasdale Mar	219294	901640	217580	902730	0.884	2.295	2.462	52	9	4322.9	0.56	0.0	2.5	Francis	97.7	89.7	2.5	1.3	1.21	30	2.58	0.77	0.1811	23
Argyll and Bute	Allt Dhoirrean	215556	732418	215648	730935	1.578	2.130	2.460	50	9	4143.6	0.30	0.2	1.7	Pelton	199	182	1.7	1	1.09	10	1.095	0.11	0.0012	2
Highland	Falls of Pattack	255419	787316	256660	790237	2.434	7.889	2.454	75	16	10325	0.48	3.5	3.6	Francis	69.5	62.5	3.6	2.5	4.76	25	9.731	2.24	0.4642	83
Highland	Allt Glac na Doimhne	237156	828476	237765	830295	0.909	2.594	2.443	55	10	4629.4	0.58	3.3	2.4	Pelton	101	92.8	2.4	1.3	1.24	30	2.741	0.76	0.1632	29
Highland	Lochan Fa¨ith an Leathaid	228982	929040	227063	930540	2.18	4.253	2.442	65	13	6410.5	0.34	8.7	12.7	Pelton	267	238	2.6	1	1.16	10	1.189	0.24	0.0486	6
Perth and Kinross	Acharn Burn	275871	742131	275609	743908	1.42	2.634	2.436	55	10	4667.3	0.38	5.0	2.0	Pelton	219	206	2.0	1	0.87	15	1.241	0.22	0.0383	13
Highland	Loch Kirkaldy	292948	841237	293066	841525	1.182	4.729	2.432	67	13	6914.5	0.67	9.4	0.4	Kaplan	13.2	11.2	0.4	3	12.5	40	32.98	11.2	2.7437	518
Stirling	Keltie Water	263980	710046	265231	707892	3.278	7.103	2.429	73	16	9462.3	0.33	1.2	3.2	Francis	111	107	3.2	2.5	3.71	15	5.003	0.76	0.1228	32
Stirling	Allt Coire Chaorach	246062	724905	245456	727419	3.179	5.390	2.421	69	14	7616	0.27	10.0	3.1	Pelton	280	254	3.1	1.2	1.59	10	1.597	0.11	0.0144	6
Argyll and Bute	Airigh nan Lochan	207618	747225	205886	747854	2.733	4.799	2.416	67	13	6977.1	0.29	11.9	3.1	Pelton	204	188	2.1	1.3	1.85	10	1.876	0.22	0.0414	10
Stirling	Allt a' Choire Ghlais	254214	735132	254355	735066	3.207	5.769	2.410	70	15	8015.5	0.29	0.3	0.2	Kaplan	20	17	0.2	3	22.2	10	22.46	3.16	0.4986	112
Aberdeenshire	Loch Kinord	341436	798105	341751	797854	0.903	4.069	2.407	64	12	6186.4	0.78	1.3	0.4	Kaplan	10.6	7.58	0.4	3	14.4	55	68.57	19	4.2803	1004
Highland	Allt Raon a' Chroisg	218546	888760	217205	888390	1.073	1.506	2.401	43	7	3429.5	0.36	0.5	1.7	Pelton	268	242	1.7	0.7	0.55	10	0.573	0.15	0.0341	4
Highland	Allt Toll a' Mhuic	223194	840373	222486	839140	1.594	2.036	2.392	50	9	3992	0.29	0.0	1.6	Pelton	210	196	1.6	1	1.02	10	1.036	0.12	0.0187	4
Highland	Abhainn Ghardail	183511	754738	183539	753318	1.4	2.279	2.383	52	9	4245.9	0.35	0.0	2.2	Pelton	169	154	2.2	1.1	1.15	15	1.512	0.15	0.0125	6
Highland	Allt na Fea rna	232618	811989	232448	813648	1.008	1.792	2.376	47	8	3718.4	0.42	0.6	2.3	Pelton	183	174	2.0	1	0.72	15	0.946	0.25	0.0566	9
Highland	Allt an Eas Dhuibh	214136	832992	214124	831142	2.62	4.426	2.348	66	13	6526.4	0.28	8.7	12.4	Pelton	260	238	2.2	1.1	1.4	10	1.4	0.11	0.0046	3
Highland	Allt Easgadill	179121	758793	178787	759747	0.845	1.164	2.331	38	6	3010	0.41	0.0	1.1	Pelton	196	187	1.1	0.8	0.56	10	0.591	0.2	0.0459	4
Highland	Allt an Reinidh	235736	936803	234544	936121	1.311	1.762	2.328	47	8	3649.2	0.32	1.5	1.7	Pelton	282	268	1.5	0.8	0.61	10	0.622	0.11	0.019	3
Highland	Allt Choille-rais	220538	776035	220757	777400	1.905	3.049	2.302	59	11	5012.2	0.30	8.6	2.2	Pelton	290	273	1.6	0.9	0.88	10	0.88	0.11	0.0055	4
D&G	Archer Beck	337564	580553	337427	580406	0.92	3.325	2.296	61	12	5303.8	0.66	1.2	0.4	Kaplan	10.1	8.83	0.2	3	12.5	40	40.6	10.4	1.9307	467
Argyll and Bute	River Noe	207605	733258	204895	734197	1.659	3.810	2.266	64	12	5802.3	0.40	3.9	3.2	Pelton	156	140	3.2	1.3	1.51	20	2.498	0.3	0.0162	9
Highland	Allt Ladaidh	222880	799477	223309	801684	1.324	3.126	2.254	60	11	5058.3	0.44	3.4	3.2	Pelton	140	123	2.7	1.2	1.36	20	2.39	0.41	0.0692	15
Highland	Allt Camas a' Choirce	177343	762141	176422	760699	1.329	2.306	2.239	54	10	4166.8	0.36	0.2	2.4	Pelton	172	159	2.4	1.1	1.06	15	1.403	0.18	0.0235	7
Highland	Allt a' Chaorainn	219878	750035	219556	751034	2.455	4.803	2.215	69	14	6829.9	0.32	6.3	1.2	Francis	70.1	68.2	1.2	2.5	4.4	15	5.717	0.61	0.0213	15
North Ayrshire	Greeto Water	223138	660570	221052	659200	1.011	2.389	2.213	55	10	4236.1	0.48	0.4	3.8	Pelton	233	214	3.8	0.9	0.59	20	1.115	0.25	0.054	9
Argyll and Bute	Kames River	199742	710299	198176	710466	1.099	1.735	2.199	48	8	3523.2	0.37	0.4	2.0	Pelton	202	189	1.8	0.9	0.73	15	1.014	0.18	0.0404	6
Highland	Allt Cailtidh	260107	820258	259557	822000	0.98	2.098	2.197	52	9	3910.8	0.46	2.2	2.2	Pelton	160	147	2.2	1	0.84	15	1.103	0.34	0.0916	12
Highland	Abhainn an Fhasaigh	202079	866327	201075	865565	1.167	2.019	2.186	52	9	3817.9	0.37	1.4	3.2	Pelton	133	123	1.4	1.1	1.2	15	1.604	0.27	0.0386	9
Moray	Lochan Uaine	314727	815253	315806	816338	1.075	3.722	2.183	64	13	5645.2	0.60	13.5	2.3	Pelton	101	95	1.9	1.4	1.44	30	3.038	1	0.2453	45
Highland	Allt Garbh-choire	218626	836768	219481	838006	1.539	2.065	2.172	52	9	3857.2	0.29	0.0	1.8	Pelton	215	201	1.8	1	0.97	10	0.974	0.11	0.0154	3

Run-of-River Sites (5% Discount Rate)

County	River	Intake Easting	Intake Northing	Power house Easting	Power house Northing	Power (MW)	Total cost (M£)	NPV (M£)	LEC (£/MWh)	Discounted Payback Period	Energy production (MWh/year)	CF	Line distance (km)	Road distance (km)	Turbine type	Gross Head (m)	Net Head (m)	Penstock Length (km)	Penstock diameter (m)	Qd (m^3s^{-1})	Qd (FDC percentile)	Q10 (m^3s^{-1})	Q50 (m^3s^{-1})	Q90 (m^3s^{-1})	Catchmnet area (km^2)
East Ayrshire	Cessnock Water	254125	626300	253724	625815	1.212	3.886	2.146	65	13	5793.7	0.55	2.6	1.2	Francis	33.7	31.2	1.2	2.5	4.93	30	10.39	3.08	0.4708	158
Highland	Allt Mar	175362	845343	172621	846583	1.635	4.271	2.144	67	13	6205.1	0.43	11.6	4.2	Pelton	290	255	3.8	0.9	0.8	15	1.074	0.28	0.07	7
Stirling	Auchinllylinn Spout	275597	684354	279112	683269	0.862	3.808	2.122	65	13	5691.1	0.75	2.7	4.7	Pelton	115	107	4.7	1.4	1.01	55	4.343	1.29	0.2212	64
Highland	Meeting of Three Waters	218264	756237	216990	756547	1.391	2.893	2.117	60	11	4704.1	0.39	5.2	2.0	Pelton	120	111	1.6	1.3	1.6	20	2.711	0.29	0.0209	11
Argyll and Bute	Allt Chaluim	224037	721528	224488	720509	1.6	3.536	2.105	64	12	5386.9	0.38	8.2	6.3	Pelton	131	120	1.6	1.3	1.7	20	3.005	0.32	0.0595	14
Highland	Allt Seanabhaile	239440	826730	240808	829657	1.264	3.094	2.064	62	12	4881	0.44	5.4	3.9	Pelton	302	268	3.9	0.8	0.59	15	0.778	0.21	0.0455	10
Highland	Allt a' Mhadaidh	222241	874440	223417	875767	1.253	2.634	2.033	59	11	4363.1	0.40	0.6	2.7	Pelton	132	117	2.5	1.2	1.36	15	1.802	0.37	0.0734	9
Stirling	Allt Lebhain	250822	736942	252457	736313	2.328	6.490	2.029	74	16	8500.8	0.42	0.2	2.0	Francis	41.2	37	2.0	3	7.85	25	17.19	2.45	0.3808	73
Highland	Falls of Balgy	185108	853450	184738	854570	1.851	4.691	1.980	70	15	6531.8	0.40	3.5	1.6	Francis	47.7	45.1	1.4	2.6	5.08	20	8.204	1.71	0.3123	55
Highland	Loch an Fhamhair	196582	887699	195298	889610	1.484	3.601	1.972	66	13	5356.2	0.41	7.6	2.8	Pelton	151	134	2.6	1.2	1.4	15	1.845	0.41	0.0797	15
Highland	Allt Baile nan Carn	227539	814681	227456	812989	0.836	1.544	1.966	48	8	3141.5	0.43	0.4	2.2	Pelton	179	169	2.0	0.9	0.62	15	0.824	0.22	0.0515	7
Highland	River Etive	215400	749062	215146	748637	1.817	5.209	1.957	72	15	7071.9	0.44	10.7	0.9	Francis	25.9	24.2	0.5	3	9.69	30	26.15	3.71	0.5185	115
Highland	Allt nan Carnan	187945	841869	189696	839759	1.315	2.844	1.945	61	12	4521.9	0.39	1.2	4.3	Pelton	303	259	4.3	0.8	0.63	15	0.845	0.16	0.0348	4
North Ayrshire	Garbh Allt	197393	638408	198337	638676	1.378	1.930	1.944	53	9	3540.2	0.29	2.4	3.3	Pelton	203	190	1.1	0.9	0.91	10	0.919	0.11	0.0174	4
Highland	Allt an Eilein Ghuirm	239700	871255	239809	869409	0.701	2.052	1.942	55	10	3669.9	0.60	0.0	2.1	Francis	75.9	68.4	2.1	1.3	1.26	35	3.395	0.9	0.1783	35
Highland	Loch Garbhaig	189803	870245	189508	871234	0.736	1.124	1.941	41	7	2672.2	0.41	0.0	1.3	Pelton	171	160	1.3	0.8	0.57	15	0.771	0.19	0.0429	5
Highland	Allt Ruigh na Sraine	292485	804707	292642	807896	1.024	3.806	1.920	67	13	5537	0.62	3.9	4.4	Pelton	130	110	4.4	1.2	1.18	35	3.754	0.8	0.1774	36
Highland	Allt Cheanna Mhuir	210578	792612	210528	791469	1.532	2.863	1.919	62	12	4523.2	0.34	10.0	1.3	Pelton	251	239	1.3	0.9	0.8	10	0.83	0.19	0.0427	4
Perth and Kinross	Allt Bhaic	283240	765573	283546	765563	0.863	3.498	1.919	66	13	5205.2	0.69	3.8	0.3	Kaplan	10.8	9.58	0.3	3	10.8	45	40.36	10.4	2.1832	453
Highland	Abhainn Thra il	192145	853746	191188	854898	1.315	3.676	1.917	66	13	5394.1	0.47	9.5	2.4	Pelton	109	105	1.9	1.6	1.59	25	3.255	0.57	0.1027	12
D&G	River Cree	232409	576677	234941	576388	2.607	9.403	1.894	80	19	11528	0.50	11.8	4.0	Francis	71.8	63.3	4.0	2.5	5.03	20	7.336	2.6	0.5072	86
Highland	Lochan na Cruaiche	172235	777078	171955	778517	0.892	1.348	1.882	46	8	2868	0.37	0.2	1.6	Pelton	224	213	1.6	0.8	0.52	15	0.686	0.11	0.0194	5
Argyll and Bute	Abhainn Strathainn	185094	673366	186194	674116	0.893	1.425	1.879	47	8	2948.4	0.38	0.2	1.5	Pelton	158	146	1.5	0.9	0.77	15	1.017	0.19	0.0384	7
Argyll and Bute	Abhainn Doire Dhubhaig	149911	734119	149145	735838	1.248	1.999	1.874	55	10	3560.9	0.33	0.7	2.1	Pelton	208	187	2.1	0.9	0.84	10	0.85	0.14	0.0203	5
Highland	Allt Coire nam Bra than	231647	840490	231959	839930	1.142	1.322	1.842	46	8	2810	0.28	0.2	0.7	Pelton	176	172	0.7	1	0.83	10	0.846	0.1	0.0207	3
East Ayrshire	Cessnock Water	256174	626099	255786	626356	0.936	2.790	1.833	62	12	4379.8	0.53	3.2	0.5	Francis	27.2	26.3	0.5	2.5	4.59	30	9.686	2.87	0.4396	146
Highland	Allt Dubh Ca¹il na Creige	248353	809974	247598	811742	0.958	2.420	1.824	59	11	3975.3	0.47	1.4	2.7	Pelton	100	91.1	2.3	1.3	1.33	20	2.24	0.53	0.1224	20
Highland	Abhainn Righ	204217	762737	203049	762957	1.119	2.085	1.808	56	10	3604	0.37	0.0	2.6	Pelton	100	95.1	1.5	1.4	1.49	20	2.65	0.21	0.0248	15
Highland	Allt Goibhre	245214	849380	247965	851531	1.081	3.287	1.787	66	13	4878.8	0.52	1.8	4.3	Pelton	152	125	4.3	1.1	1.09	20	1.695	0.47	0.0827	24
Highland	Lochan na Craoibhe	170683	786537	169482	785090	1.031	1.782	1.779	53	9	3256.5	0.36	0.0	2.3	Pelton	220	208	2.3	0.9	0.62	15	0.835	0.13	0.0261	4
Highland	River Broom	220150	881987	219430	881380	0.86	1.093	1.776	42	7	2513.8	0.33	0.0	1.0	Pelton	230	224	1.0	0.8	0.48	10	0.491	0.11	0.0229	3
Highland	Allt Eiteachan	257618	887700	260452	889514	0.807	2.271	1.774	59	11	3778.1	0.53	0.0	4.1	Pelton	169	139	4.1	0.9	0.73	20	1.108	0.35	0.0762	15
Highland	Loch Coire Chuir	250330	785988	249801	787179	0.911	2.043	1.773	56	10	3531.9	0.44	0.9	1.6	Francis	89.5	82.9	1.6	1.3	1.35	25	3.146	0.48	0.0747	25
Highland	Allt an Tomain Odhair	188452	809295	187229	809306	3.17	7.317	1.769	78	18	9192.7	0.33	22.6	3.3	Francis	107	105	1.6	2.5	3.67	15	4.867	0.72	0.0932	22
Stirling	Allt Leacachan	262699	727936	261698	724995	1.301	3.137	1.747	65	13	4687.3	0.41	3.3	3.6	Pelton	199	172	3.6	1	0.95	15	1.343	0.28	0.0472	12
Highland	Allt Mar Gisgil	218302	941760	217452	941729	1.062	2.641	1.732	62	12	4144.3	0.45	8.3	1.6	Pelton	100	97.2	1.0	1.4	1.38	15	1.82	0.54	0.1229	20
Highland	Allt Mheuran	214628	744245	213574	746049	2.193	4.172	1.726	70	15	5783.7	0.30	13.8	2.9	Pelton	319	287	2.4	0.9	0.96	10	0.964	0.11	0.0057	2
Highland	Allt Bruthach an Easain	199738	876915	198893	876300	1.884	3.658	1.692	69	14	5205.5	0.32	12.9	12.9	Pelton	269	255	1.2	0.9	0.93	10	0.957	0.18	0.042	5
Highland	Allt na Cloiche	181745	759389	181875	760269	0.665	0.980	1.679	41	7	2319.6	0.40	0.0	1.1	Pelton	179	173	1.1	0.8	0.48	15	0.637	0.14	0.0312	4
Scottish Borders	Whiteadder Water	381582	656255	381942	656004	0.825	2.436	1.679	61	12	3883.4	0.54	0.4	0.8	Francis	23.1	22.1	0.5	2.5	4.91	30	9.537	3.15	0.4745	272

Run-of-River Sites (5% Discount Rate)

County	River	Intake Easting	Intake Northing	Power house Easting	Power house Northing	Power (MW)	Total cost (M£)	NPV (M£)	LEC (£/MWh)	Discounted Payback Period	Energy production (MWh/year)	CF	Line distance (km)	Road distance (km)	Turbine type	Gross Head (m)	Net Head (m)	Penstock Length (km)	Penstock diameter (m)	Qd (m^3s^{-1})	Qd (FDC percentile)	Q10 (m^3s^{-1})	Q50 (m^3s^{-1})	Q90 (m^3s^{-1})	Catchmnet area (km^2)
Highland	Loch Bad a' Chratha	178252	873355	178289	873669	1.03	2.889	1.669	65	13	4361.9	0.48	5.9	0.4	Francis	31.1	30.6	0.4	2.5	4.29	25	7.618	2.36	0.552	55
Highland	Drundreggan Reservoir	234754	816313	235399	815718	0.696	1.134	1.666	45	7	2475.9	0.41	0.0	1.1	Pelton	130	122	1.1	0.9	0.71	15	0.986	0.22	0.0431	9
Highland	Allt a' Mha¨il	204589	803019	204105	802235	1.29	1.919	1.651	57	10	3307.1	0.29	3.1	1.0	Pelton	180	176	1.0	1.1	0.92	10	0.927	0.1	0.0083	3
D&G	Carron Water	286333	598013	286253	597736	0.836	3.505	1.634	68	14	4997.2	0.68	3.8	0.7	Kaplan	10.5	9.27	0.3	3	10.8	45	46.99	10.1	1.5246	492
D&G	Water of Trool	236951	581034	237120	578528	2.751	8.344	1.620	80	19	10184	0.42	13.2	3.0	Francis	70.3	63.2	3.0	2.5	5.32	20	9.087	1.93	0.388	74
Highland	Loch na Da il	208791	913713	207991	912722	0.568	1.735	1.604	55	10	3074.4	0.62	0.0	2.0	Francis	60.5	54.7	1.6	1.3	1.29	40	4.069	1.03	0.1982	40
Perth and Kinross	Allt Coire Cruach Sneachda	266663	755306	267329	757435	1.347	2.543	1.595	63	12	3935.3	0.33	1.4	2.5	Pelton	169	153	2.5	1.1	1.11	15	1.629	0.18	0.0316	15
Highland	Allt Coire an Lochain	212589	828863	212456	829776	1.985	3.569	1.571	69	14	5018.7	0.29	10.4	15.9	Pelton	262	244	1.2	0.9	1.03	10	1.034	0.11	0.0137	5
Argyll and Bute	Abhainn na h-Uamha	151775	735815	150720	736805	0.894	1.420	1.567	51	9	2708.1	0.35	0.0	1.6	Pelton	176	165	1.6	0.9	0.68	15	0.873	0.1	0.0124	4
Highland	Allt Garbh	218186	820200	217953	822427	1.541	3.959	1.555	71	15	5425.9	0.40	10.1	2.9	Pelton	159	142	2.7	1.2	1.37	20	2.479	0.31	0.0516	12
Highland	Allt Choire a' Bhalachain	211799	798729	213291	800371	0.772	2.024	1.552	59	11	3345.7	0.49	0.9	2.9	Pelton	121	103	2.5	1	0.94	20	1.68	0.39	0.0884	9
Highland	Allt Gharagain	213021	852038	212799	854069	1.011	1.930	1.535	58	11	3231.5	0.36	0.8	2.3	Pelton	189	171	2.3	0.9	0.74	15	1.014	0.16	0.0277	6
Highland	Loch Coire nan Arr	181109	841666	182046	840649	1.415	3.172	1.535	68	14	4565.1	0.37	7.5	1.6	Pelton	119	109	1.6	1.3	1.65	15	2.118	0.33	0.0385	9
Argyll and Bute	Loch Airigh na Creige	201140	703711	202216	702337	0.863	1.471	1.527	53	9	2732.2	0.36	0.2	2.3	Pelton	240	215	2.1	0.7	0.5	15	0.69	0.11	0.0274	4
Highland	River Rha	140406	865336	139455	864162	0.671	1.447	1.526	52	9	2705.9	0.46	0.8	1.7	Pelton	122	109	1.7	0.9	0.77	15	1.009	0.3	0.0685	11
Highland	Lochan Torr a' Choit	193657	808170	193451	807714	2.184	4.204	1.523	72	15	5664.3	0.30	15.8	10.1	Pelton	152	146	0.6	1.3	1.9	10	1.917	0.24	0.0251	8
Highland	Allt an Fhaing	184784	759750	184826	760639	0.864	1.171	1.519	48	8	2403.9	0.32	0.4	1.1	Pelton	221	214	1.1	0.8	0.5	10	0.516	0.1	0.0239	2
Highland	Allt Coir' a' Chliabhain	233270	876386	234198	876166	0.874	1.426	1.515	52	9	2674.4	0.35	1.6	2.4	Pelton	180	173	1.1	0.9	0.63	15	0.852	0.12	0.0246	5
Stirling	Lochan a' Craoi	238277	728070	237370	726864	1.594	2.790	1.493	66	13	4123.3	0.30	6.4	1.7	Pelton	207	191	1.7	1	1.05	10	1.072	0.17	0.0357	5
Highland	Allt Chna imhean	203627	863552	202999	863305	0.794	1.026	1.477	45	7	2216.5	0.32	0.2	1.4	Pelton	190	178	0.8	0.7	0.56	10	0.567	0.11	0.0212	4
Angus	Burn of Glenmoye	338970	761615	339662	759733	1.646	6.392	1.476	78	18	7978.8	0.55	6.8	2.7	Francis	48.9	43.9	2.7	2.5	4.65	30	10.9	2.85	0.5741	163
Highland	Loch Beag	263251	885543	264397	886659	0.652	1.402	1.473	52	9	2617.4	0.46	0.2	1.8	Pelton	130	118	1.8	0.9	0.69	15	0.878	0.27	0.0467	15
South Lanarkshire	Avon Water	276518	648697	275248	650730	1.634	7.424	1.470	80	19	9083.1	0.63	0.5	3.3	Francis	39.7	33.9	3.3	2.8	6.06	40	15.33	4.99	0.7704	240
Highland	River Glass	255395	865501	258937	865576	0.723	2.735	1.468	66	13	4045.7	0.64	0.2	4.4	Pelton	106	92.6	4.2	1.2	0.98	35	2.29	0.72	0.141	37
Highland	Allt a' Choire Dhomhain	215800	828684	215606	830176	1.919	3.531	1.467	70	15	4899.9	0.29	7.2	14.4	Pelton	251	236	1.8	1	1.03	10	1.031	0.11	0.0063	5
Highland	Lochan Tain Mhic Dhughaill	183880	785925	183311	785196	1.14	1.911	1.463	59	11	3155.9	0.32	3.7	9.0	Pelton	262	245	1.1	0.7	0.58	10	0.592	0.1	0.0186	3
Na h-Eileanan an Iar	Loch Faoghail an Tuim	120709	928537	121632	929664	1.061	4.026	1.455	72	15	5422.6	0.58	0.0	1.8	Francis	31.1	27.8	1.6	2.5	4.9	35	10.92	3.66	0.8224	105
Highland	Abhainn Bhuachaig	191689	844112	192492	842802	1.001	1.952	1.447	60	11	3188.8	0.36	0.0	2.3	Pelton	147	128	2.3	1	0.98	15	1.328	0.18	0.0311	6
Highland	Allt a' Choire Dhomdain	199714	815781	201091	816877	2.181	4.406	1.432	74	16	5812.7	0.30	16.6	4.5	Pelton	311	283	2.1	0.9	0.97	10	0.971	0.11	0.0001	3
Highland	Loch Farr	271592	830924	268995	831447	0.626	1.737	1.425	58	11	2941.2	0.54	1.4	3.1	Pelton	177	157	3.1	0.8	0.49	20	0.747	0.26	0.0621	14
Highland	Loch Ness	244218	813900	243823	814589	1.012	1.831	1.417	59	11	3035.8	0.34	3.7	4.8	Pelton	181	177	1.0	1	0.72	10	0.732	0.18	0.0297	10
Highland	Allt nan Adag	261833	820638	260598	823307	0.748	2.238	1.410	63	12	3468	0.53	1.5	4.2	Pelton	205	177	4.0	0.8	0.52	20	0.814	0.27	0.0729	5
Highland	Allt Taige	217856	832198	218696	831141	1.477	2.421	1.407	64	13	3662	0.28	4.1	4.8	Pelton	221	212	1.5	1	0.88	10	0.888	0.1	0.017	4
Highland	Easan Dorcha	200411	852672	202148	852988	1.244	2.581	1.404	66	13	3831.5	0.35	4.1	2.2	Pelton	166	155	2.2	1.1	1.01	15	1.354	0.19	0.0375	6
Highland	Allt a' Choire	188007	785611	186041	784905	1.866	3.512	1.402	71	15	4830.2	0.30	3.2	12.9	Pelton	190	164	2.4	1.1	1.45	10	1.448	0.13	0.0037	6
Argyll and Bute	River Liver	210823	734467	206632	735601	1.667	4.018	1.395	73	16	5368.1	0.37	5.9	4.7	Pelton	313	274	4.7	0.9	0.76	15	1.002	0.15	0.0182	3
Highland	Allt Deamhaidh	268732	811869	268058	815144	1.433	5.021	1.383	76	17	6436.4	0.51	12.7	4.4	Pelton	168	145	4.4	1.2	1.25	20	2.011	0.61	0.1624	25
Highland	Allt a Chrom-uillt	230905	882886	231450	883504	1.444	2.789	1.375	67	14	4032.7	0.32	10.1	3.0	Pelton	193	186	0.9	1	0.97	10	1.011	0.21	0.0549	6
Highland	Loch Garraidh Mhair	217490	891020	216503	890434	0.52	0.875	1.369	43	7	1972.6	0.43	0.4	1.3	Pelton	222	209	1.3	0.6	0.31	15	0.408	0.11	0.0288	4
Stirling	River Dochart	251499	731092	251379	729492	1.079	2.123	1.368	63	12	3312.7	0.35	4.2	1.9	Pelton	229	219	1.9	0.9	0.62	15	0.9	0.13	0.0267	6

Run-of-River Sites (5% Discount Rate)

County	River	Intake Easting	Intake Northing	Power house Easting	Power house Northing	Power (MW)	Total cost (M£)	NPV (M£)	LEC (£/MWh)	Discounted Payback Period	Energy production (MWh/year)	CF	Line distance (km)	Road distance (km)	Turbine type	Gross Head (m)	Net Head (m)	Penstock Length (km)	Penstock diameter (m)	Qd (m^3s^{-1})	Qd (FDC percentile)	Q10 (m^3s^{-1})	Q50 (m^3s^{-1})	Q90 (m^3s^{-1})	Catchmnet area (km^2)
Highland	Loch Eas na Maoile	238690	933679	238403	933054	0.603	1.472	1.364	55	10	2610	0.49	0.3	0.8	Francis	50.5	48.5	0.8	1.5	1.55	30	3.853	0.76	0.1475	22
Argyll and Bute	Abhainn na Ca¹ile	182939	669202	183833	667212	1.102	3.113	1.349	70	14	4361.3	0.45	1.8	3.3	Pelton	128	110	3.3	1.2	1.27	20	2.2	0.41	0.0813	16
Highland	Allt Raon a' Chroisg	218362	889551	217229	889934	0.668	1.069	1.347	48	8	2165.5	0.37	0.0	1.7	Pelton	203	189	1.5	0.7	0.44	15	0.605	0.1	0.019	4
Highland	Achriesgill Water	226761	952880	225606	952550	0.545	1.206	1.333	51	9	2300.9	0.48	0.5	1.4	Pelton	107	101	1.4	1	0.67	20	1.059	0.29	0.059	10
Highland	Loch Coire a' Bhaic	223562	930338	223813	931968	1.29	3.512	1.322	72	15	4769.3	0.42	11.9	2.3	Pelton	148	133	2.0	1.1	1.23	15	1.616	0.39	0.0831	12
Highland	Allt Leacachain	223874	877292	223253	876201	0.675	1.117	1.300	50	9	2180.7	0.37	0.3	1.4	Pelton	179	170	1.4	0.8	0.49	15	0.687	0.12	0.0241	4
Highland	Allt Mar	264091	823131	262559	825115	0.61	1.480	1.288	56	10	2561.4	0.48	0.5	2.9	Pelton	203	177	2.9	0.7	0.43	15	0.558	0.19	0.0496	7
Highland	Allt Achaidh Luachraich	225739	804667	224649	802941	0.614	1.480	1.287	56	10	2561	0.48	0.2	3.1	Pelton	229	208	3.1	0.7	0.36	20	0.645	0.15	0.0341	5
Highland	Allt Coire Mhuilidh	235079	865449	235399	863965	0.583	1.178	1.262	52	9	2218.2	0.43	0.2	1.7	Pelton	150	139	1.7	0.8	0.52	15	0.691	0.19	0.0409	7
Highland	Loch Ard a' Phuill	169868	773366	170055	772829	0.662	0.880	1.261	45	8	1897.4	0.33	0.2	0.6	Pelton	168	164	0.6	0.8	0.5	10	0.511	0.1	0.0185	3
Argyll and Bute	Allt na Cuile Riabhaiche	206536	720109	206588	720979	0.653	0.994	1.258	48	8	2016.4	0.35	0.2	1.3	Pelton	181	175	1.1	0.8	0.46	15	0.644	0.1	0.0242	3
Highland	Allt Tigh Naill	274203	898618	275370	898870	0.547	1.823	1.255	61	12	2905.1	0.61	1.3	1.5	Francis	60.2	55	1.5	1.3	1.24	35	2.731	0.91	0.1538	51
Highland	Loch a' Bhainne	227519	804209	227878	803100	0.54	0.961	1.253	47	8	1977.8	0.42	0.4	1.7	Pelton	170	159	1.3	0.7	0.42	15	0.565	0.14	0.0323	5
Stirling	Allt Essan	243569	728691	244637	728113	1.785	3.382	1.252	72	15	4577.7	0.29	9.7	1.8	Pelton	186	172	1.6	1.1	1.32	10	1.34	0.2	0.0419	6
Highland	Abhainn a' Choire	236743	926415	236509	925578	0.532	0.921	1.246	47	8	1929.6	0.41	1.0	1.2	Pelton	178	171	1.0	0.7	0.38	15	0.538	0.13	0.0319	3
Highland	Allt Coire nam Plaidean	254824	782882	254786	786362	2.793	8.761	1.243	83	20	10347	0.42	0.2	4.5	Francis	80.1	71.5	4.5	2.5	4.76	20	8.148	1.73	0.3607	63
Highland	Allt Meallan Gobhar	183305	844659	184049	844066	0.82	1.744	1.217	61	11	2791.4	0.39	3.3	1.2	Pelton	124	116	1.2	1	0.89	15	1.15	0.23	0.0387	6
Perth and Kinross	Allt Caochan an t-Seilich	255608	759492	254515	758168	0.603	1.582	1.204	59	11	2607.9	0.49	0.2	2.1	Pelton	100	93	2.1	1.1	0.81	20	1.322	0.35	0.0639	18
Highland	Lochan na Bearta	199788	883946	199477	885136	1.334	3.734	1.195	74	16	4911.7	0.42	11.4	8.2	Pelton	100	95.2	1.4	1.5	1.78	20	2.944	0.5	0.0798	16
Scottish Borders	Ettrick Water	338426	624096	339043	624664	1.508	5.521	1.192	79	18	6829.2	0.52	9.8	1.1	Francis	29	26.6	1.1	2.9	7.28	30	18.95	4.12	0.7057	192
East Ayrshire	River Ayr	250046	625180	249588	625234	0.693	2.337	1.184	67	13	3403.3	0.56	0.0	0.7	Francis	20	19	0.5	2.5	4.92	35	11.84	3.54	0.5365	184
Perth and Kinross	Allt a' Chobhair	261027	746110	261229	747286	1.998	3.448	1.182	73	16	4595.5	0.26	8.5	1.4	Pelton	161	152	1.4	1.3	1.67	10	1.679	0.14	0.0202	12
North Ayrshire	Smallburn Resr	230672	657640	231572	656380	0.873	2.235	1.174	66	13	3286.6	0.43	3.2	2.3	Pelton	115	103	1.9	1.1	1.07	20	2.011	0.32	0.0773	11
Highland	Garbh Allt	248566	887920	247212	889693	1.253	3.812	1.168	75	16	4975.7	0.45	11.3	3.2	Pelton	164	146	3.0	1.1	1.08	15	1.4	0.41	0.087	16
Highland	Allt Eindart	289911	788644	287046	789010	2.5	8.544	1.157	83	20	10049	0.46	13.2	8.0	Francis	80.9	76.4	3.3	2.5	3.99	20	6.515	1.9	0.4987	70
Highland	Allt Fhiodhan	212587	756544	212070	757053	1.619	3.962	1.154	75	17	5125.3	0.36	2.6	1.2	Francis	48	46	1.2	2.5	4.35	20	7.251	0.88	0.0538	31
Highland	Allt Horn	232116	943170	231263	942597	0.77	1.504	1.145	59	11	2479.9	0.37	2.0	1.8	Pelton	132	121	1.2	0.9	0.79	15	1.063	0.17	0.0286	5
Highland	Allt a' Ghiubhais	187335	782270	187844	781659	0.79	1.435	1.143	58	11	2403.9	0.35	0.2	1.2	Pelton	108	97.2	1.2	1	1.02	15	1.352	0.15	0.0148	6
Highland	Allt a' Choire Cha rnaig	192085	785448	191083	783782	0.94	2.514	1.138	69	14	3559.1	0.43	2.7	2.3	Pelton	101	92.7	2.3	1.3	1.28	25	2.669	0.32	0.0066	9
Highland	Loch na Plangaid	241766	842496	241013	841004	0.526	1.315	1.133	57	10	2267.5	0.49	0.0	1.9	Pelton	107	100	1.9	1	0.65	20	1.036	0.28	0.0485	12
Highland	Allt a' Choire Dhuibh	189066	781279	189946	780578	0.69	1.740	1.127	62	12	2719.3	0.45	0.4	1.3	Francis	64.9	58.9	1.3	1.3	1.45	30	3.874	0.46	0.0395	14
Perth and Kinross	Spout Rolla	274901	729146	274188	727561	0.977	1.763	1.120	63	12	2738.7	0.32	0.6	2.0	Pelton	185	177	2.0	1	0.69	15	1.002	0.1	0.0178	6
Highland	Allt an Dubh Choirein	186177	766570	185746	765359	1.281	2.388	1.117	68	14	3408.1	0.30	4.4	4.3	Pelton	191	169	1.7	0.9	0.95	10	0.959	0.11	0.0102	4
Highland	Allt an Tireidh	244206	932199	244573	930422	1.069	2.616	1.116	70	14	3652.3	0.39	4.3	5.0	Pelton	133	119	2.1	1.1	1.13	15	1.48	0.29	0.0584	7
Highland	Allt na Mucaireachd	173714	750127	172698	750295	0.399	1.478	1.113	59	11	2427.7	0.69	0.3	1.4	Francis	45.7	41.2	1.4	1.3	1.22	50	5.407	1.38	0.2789	34
Highland	Allt Guibhsachain	207863	755850	208084	758042	1.098	2.448	1.111	69	14	3467.5	0.36	3.0	2.5	Pelton	157	136	2.5	1	1.02	15	1.339	0.16	0.007	5
Scottish Borders	Ettrick Water	343303	627963	343604	627694	0.888	3.086	1.109	73	15	4151.3	0.53	3.9	0.4	Francis	20.4	19.5	0.4	2.7	6.11	35	19.81	3.91	0.6213	231
Highland	Allt Innis a' Mhuilt	222036	837176	222673	838400	0.709	1.297	1.103	57	10	2225.8	0.36	0.5	1.6	Pelton	155	138	1.6	0.8	0.64	15	0.911	0.13	0.0209	4
Argyll and Bute	Kilduskland Resr	183719	686530	185372	686516	0.589	1.225	1.093	56	10	2140	0.41	0.4	2.1	Pelton	205	190	2.1	0.7	0.38	15	0.532	0.13	0.0269	3
Argyll and Bute	Allt Dubh	185284	677586	185945	677186	0.609	0.958	1.087	51	9	1848.5	0.35	0.2	0.9	Pelton	138	130	0.9	0.8	0.58	15	0.77	0.1	0.0225	4

Run-of-River Sites (5% Discount Rate)

County	River	Intake Easting	Intake Northing	Power house Easting	Power house Northing	Power (MW)	Total cost (M£)	NPV (M£)	LEC (£/MWh)	Discounted Payback Period	Energy production (MWh/year)	CF	Line distance (km)	Road distance (km)	Turbine type	Gross Head (m)	Net Head (m)	Penstock Length (km)	Penstock diameter (m)	Qd (m^3s^{-1})	Qd (FDC percentile)	Q10 (m^3s^{-1})	Q50 (m^3s^{-1})	Q90 (m^3s^{-1})	Catchmnet area (km^2)
Highland	Loch Bad na Goibhre	210432	921721	209433	922111	0.591	1.783	1.078	64	12	2728.4	0.53	0.5	1.3	Francis	55.6	52.8	1.3	1.5	1.4	30	3.267	0.8	0.1559	33
Perth and Kinross	Allt Sran an Duine	288377	772380	288960	771137	1.258	3.459	1.076	75	16	4527.4	0.41	10.2	1.6	Pelton	101	96.5	1.6	1.5	1.66	20	3.19	0.48	0.1175	15
Highland	Finiskaig River	188475	794425	187451	794685	1.884	3.826	1.074	76	17	4920	0.30	12.8	6.8	Pelton	196	183	1.4	1.1	1.3	10	1.302	0.15	0.0045	4
Highland	Allt Guibhsachain	204383	757527	204707	759619	1.318	2.903	1.074	72	15	3928.3	0.34	5.8	2.5	Pelton	170	157	2.3	1.1	1.06	15	1.387	0.13	0.0031	4
Moray	Falls of Feakirk	300788	847736	300216	849775	1.587	6.336	1.073	81	19	7615.2	0.55	8.0	2.8	Francis	58.3	55.3	2.8	2.5	3.53	25	5.869	2.19	0.4647	161
Highland	River Rha	140703	863557	139869	863781	0.521	1.345	1.068	58	11	2250.7	0.49	0.6	1.0	Francis	62.8	58.9	1.0	1.2	1.1	25	2.121	0.55	0.1107	18
Highland	Allt Daingean	224130	804210	224339	802870	0.547	1.047	1.061	53	9	1925.3	0.40	0.0	1.7	Pelton	159	139	1.7	0.7	0.49	15	0.706	0.14	0.0293	5
Argyll and Bute	Allt Eilidh	206666	752815	206648	751605	1.716	3.301	1.056	74	16	4342.1	0.29	9.1	1.4	Pelton	142	129	1.4	1.2	1.69	10	1.701	0.16	0.0188	6
Highland	Aldernaig Burn	229491	802327	229768	801039	0.529	1.383	1.044	59	11	2272.8	0.49	0.0	1.5	Francis	79.1	73	1.5	1.1	0.9	25	1.772	0.44	0.0906	17
Highland	Allt an Fhaing	191854	777008	192419	778112	0.894	1.742	1.043	64	12	2658	0.34	0.8	1.6	Pelton	108	105	1.4	1.3	1.08	15	1.415	0.15	0.0132	5
Scottish Borders	Ale Water	361361	624964	361783	625154	0.763	2.657	1.031	71	15	3632.1	0.54	4.2	0.5	Francis	26.6	26	0.5	2.5	3.8	30	7.306	2.44	0.3786	164
Highland	Allt a' Bhealaich Mhair	242623	866716	241180	867365	0.624	1.168	1.001	57	10	2009.3	0.37	0.2	1.7	Pelton	180	172	1.7	0.8	0.45	15	0.611	0.1	0.0187	7
Scottish Borders	Covenanters' Well	350647	635370	351098	635229	0.609	2.121	1.000	68	14	3032.8	0.57	0.0	0.5	Francis	21.6	21	0.5	2.5	3.87	35	9.25	2.77	0.4015	219
Argyll and Bute	Allt a Guanan	225590	701157	226380	701087	1.329	2.418	0.999	70	15	3351	0.29	6.8	0.9	Pelton	142	135	0.9	1.1	1.25	10	1.253	0.1	0.0061	4
Highland	Allt Bad an Fhliuchaidh	225969	859295	227169	860455	0.678	1.880	0.997	66	13	2771.4	0.47	1.2	3.4	Pelton	102	91.8	2.3	1.1	0.93	20	1.607	0.34	0.0589	13
Argyll and Bute	Allt Easach	170915	628166	172940	625946	0.712	2.817	0.997	73	16	3777.4	0.61	1.3	4.4	Pelton	101	86.6	4.0	1.2	1.04	30	2.696	0.65	0.1192	29
Highland	Abhainn Dheabhag	228536	822025	227656	823830	0.952	2.647	0.991	72	15	3591	0.43	7.8	3.7	Pelton	210	182	2.6	0.8	0.65	15	0.878	0.22	0.0469	7
Argyll and Bute	Allt Ghiusachan	211385	739687	209228	740187	1.839	3.805	0.989	77	17	4833	0.30	8.7	5.4	Pelton	214	196	2.5	1.1	1.18	10	1.193	0.14	0.015	4
Highland	Allt Glas Toll Beag	233453	878676	234666	878199	0.996	1.945	0.981	67	13	2829.5	0.32	3.8	2.0	Pelton	177	170	1.5	1	0.73	15	1.022	0.11	0.0205	4
Highland	Loch Dubh a' Chuail	235013	926853	236124	925881	0.637	1.307	0.977	60	11	2141.6	0.38	1.6	2.2	Pelton	207	192	1.8	0.7	0.41	15	0.566	0.11	0.0246	2
Highland	Allt Staoine	309280	922299	312042	922437	0.749	3.867	0.976	77	17	4890.3	0.75	9.8	3.7	Francis	95.6	86.3	3.7	1.3	1.07	55	3.992	1.37	0.2623	65
Stirling	Allt Gleann Auchreoch	233077	727142	233526	728610	1.03	2.263	0.974	70	14	3166.2	0.35	2.6	2.0	Pelton	120	105	1.8	1.1	1.23	15	1.668	0.19	0.0292	7
Highland	Allt Gleann a' Choire Dhomhain	199472	833103	197959	834494	1.024	2.647	0.971	72	15	3575.8	0.40	2.0	5.1	Pelton	116	104	2.4	1.2	1.25	20	2.139	0.26	0.0265	8
Perth and Kinross	Allt Leac Ghiubhais	252698	753472	254893	756217	1.129	3.903	0.966	77	18	4920.8	0.50	4.9	4.2	Pelton	137	116	4.2	1.2	1.23	25	3.059	0.47	0.0751	25
Highland	Allt Mhuic	212725	792741	212070	791286	1.663	3.352	0.962	76	17	4326.1	0.30	10.3	2.0	Pelton	199	179	1.8	1	1.17	10	1.192	0.17	0.0294	6
Perth and Kinross	Allt Eigheach	243560	762034	243568	760517	0.969	2.146	0.961	69	14	3030	0.36	2.6	2.3	Pelton	116	104	1.7	1.1	1.18	15	1.7	0.24	0.0535	11
Highland	Allt Dail a' Chuirn	230246	806372	231344	805674	0.538	1.211	0.951	59	11	2018.9	0.43	2.3	3.7	Pelton	210	192	1.5	0.6	0.35	15	0.465	0.12	0.0288	3
South Lanarkshire	Rotten Calder	266560	656324	267632	656926	0.495	1.724	0.944	66	13	2563.6	0.59	0.4	1.8	Francis	53.7	50.1	1.6	1.4	1.23	35	2.733	0.87	0.1148	39
Highland	Allt Coire a' Mha im	212023	831444	214071	831115	1.568	3.647	0.939	77	17	4625.8	0.34	8.7	12.5	Pelton	231	222	2.3	1.1	0.89	15	1.184	0.13	0.0143	4
Argyll and Bute	Uisge Fealasgaig	152595	725053	151889	726411	0.532	1.406	0.933	62	12	2214.5	0.48	1.6	1.7	Pelton	108	102	1.7	1	0.65	20	1.061	0.26	0.0483	8
Highland	Allt Coire Ghaidheil	210866	821691	210784	820799	1.713	3.555	0.931	77	17	4520.5	0.30	13.9	3.1	Pelton	171	165	1.0	1.2	1.32	10	1.328	0.18	0.0189	5
Argyll and Bute	Erallich Water	206879	711897	208866	712347	1.069	2.353	0.928	71	15	3228.1	0.34	2.0	2.7	Pelton	160	140	2.7	1	0.96	15	1.327	0.16	0.0391	6
Perth and Kinross	Falls of Barvick	284550	725554	284996	724189	0.668	1.322	0.928	61	11	2120.3	0.36	1.4	1.8	Pelton	198	179	1.8	0.7	0.46	15	0.65	0.1	0.0182	7
Argyll and Bute	Eas a' Ghaill	222050	725672	220259	727104	1.374	3.057	0.925	75	16	3980.9	0.33	4.8	2.9	Pelton	169	150	2.7	1.1	1.16	15	1.557	0.13	0.0193	7
Highland	Allt Garbh	244294	838238	245593	840033	0.456	1.200	0.903	59	11	1969.8	0.49	0.2	2.7	Pelton	159	139	2.5	0.7	0.41	20	0.68	0.17	0.0219	10
Highland	Allt na Criche	219318	850416	220077	850733	1.622	4.393	0.900	79	19	5397.6	0.38	7.6	1.4	Francis	39.9	37.6	1.0	2.5	5.4	20	8.981	1.52	0.2491	48
D&G	Black Water	262383	588569	261085	588527	0.535	1.668	0.899	66	13	2469.9	0.53	18.4	1.8	Francis	81.3	74.9	1.6	1.1	0.88	25	1.681	0.47	0.0658	22
Highland	Allt Coire nam Bra than	233056	838818	233266	839460	0.541	1.004	0.898	56	10	1756.2	0.37	0.4	1.1	Pelton	100	96.9	0.8	1	0.7	15	0.966	0.17	0.0219	11
Perth and Kinross	Water of Ruchill	272836	717533	274373	718400	1.688	5.337	0.897	81	19	6408.3	0.43	2.8	3.7	Francis	47.1	42.7	2.1	2.5	4.91	25	11.45	1.75	0.2936	80
Highland	Allt Mar na Sraine	144629	830609	144825	831406	0.357	0.676	0.893	47	8	1399.8	0.45	0.2	1.1	Pelton	141	130	0.9	0.6	0.34	15	0.454	0.13	0.028	2

Run-of-River Sites (5% Discount Rate)

County	River	Intake Easting	Intake Northing	Power house Easting	Power house Northing	Power (MW)	Total cost (M£)	NPV (M£)	LEC (£/MWh)	Discounted Payback Period	Energy production (MWh/year)	CF	Line distance (km)	Road distance (km)	Turbine type	Gross Head (m)	Net Head (m)	Penstock Length (km)	Penstock diameter (m)	Qd (m^3s^{-1})	Qd (FDC percentile)	Q10 (m^3s^{-1})	Q50 (m^3s^{-1})	Q90 (m^3s^{-1})	Catchmnet area (km^2)
Argyll and Bute	Allt nan Giuthas	219152	732817	218276	732933	1.082	1.944	0.880	69	14	2751.7	0.29	3.5	3.0	Pelton	129	119	1.0	1	1.15	10	1.159	0.11	0.0119	4
South Lanarkshire	Wellbrae Resrs	268886	659204	268669	659362	0.872	5.209	0.876	81	19	6255.2	0.82	2.9	0.5	Kaplan	10	4.82	0.3	3	22.5	55	96.56	28.4	4.2416	1704
Highland	Lan Mar	144363	852285	143226	851454	0.513	1.319	0.868	62	12	2071.5	0.46	0.0	1.9	Pelton	101	93.6	1.9	1	0.69	20	1.143	0.25	0.05	8
Argyll and Bute	Allt a' Ghlinne Dhuibh	153425	730997	153994	729635	0.69	1.414	0.865	64	12	2171.1	0.36	0.0	2.0	Pelton	135	122	1.8	0.9	0.71	15	0.903	0.12	0.008	2
Highland	Loch an Ime	171560	822290	170424	823706	0.479	1.377	0.863	63	12	2130.3	0.51	0.0	2.2	Pelton	101	94	2.2	1	0.64	25	1.316	0.28	0.0487	10
Scottish Borders	Ale Water	361923	625154	362213	625098	0.687	2.406	0.863	73	15	3235	0.54	3.9	0.6	Francis	24	23.6	0.4	2.5	3.82	30	7.328	2.45	0.3806	165
Scottish Borders	Leader Water	355983	640963	356164	640633	0.701	2.454	0.862	73	16	3285.7	0.53	2.4	0.7	Francis	22	21.3	0.4	2.5	4.37	30	8.329	2.81	0.4194	233
Highland	Loch na Maine Beag	220455	861290	221067	860557	0.367	0.707	0.858	49	8	1407.5	0.44	0.0	1.3	Pelton	142	128	1.1	0.6	0.35	15	0.47	0.13	0.0305	5
Highland	Allt a' Gharbhrain	226289	878025	227664	876581	0.89	2.317	0.857	72	15	3134.8	0.40	1.7	4.1	Pelton	107	101	2.2	1.3	1.11	20	1.91	0.26	0.0453	11
Highland	Garbh Allt	293963	912709	295044	910049	0.585	2.235	0.854	72	15	3044.5	0.59	0.2	3.9	Pelton	101	87	3.7	1.1	0.84	30	1.958	0.51	0.0767	33
Highland	Allt Coire nan Dearcag	253975	796716	252373	794985	1.195	3.536	0.853	78	18	4441.4	0.42	8.8	3.0	Pelton	150	129	3.0	1.1	1.17	15	1.653	0.37	0.0847	15
Highland	Loch Arienas	169360	752534	168884	751398	0.532	1.139	0.853	60	11	1866.4	0.40	1.3	2.7	Pelton	160	146	1.4	0.7	0.45	15	0.599	0.12	0.0237	4
Argyll and Bute	Allt Gleann Laoigh	205976	686544	205642	686160	0.612	1.059	0.837	58	11	1769.6	0.33	0.6	3.1	Pelton	101	98	0.5	1	0.78	15	1.05	0.1	0.018	5
Highland	Allt Bheargais	235595	885332	235553	884090	1.272	2.675	0.834	75	16	3501.8	0.31	9.7	1.5	Pelton	245	227	1.5	0.8	0.7	10	0.725	0.15	0.0361	3
Highland	Lochan a' Chreobhair	231623	939949	230752	940861	0.432	1.078	0.822	59	11	1778.3	0.47	0.7	2.2	Pelton	105	98.8	1.4	0.9	0.54	20	0.899	0.22	0.044	9
Highland	Allt Coire an t-Sneachda	298491	806694	298579	808931	1.269	3.225	0.808	77	17	4073.5	0.37	7.6	2.8	Pelton	167	152	2.6	1.1	1.05	15	1.467	0.23	0.052	14
Highland	Allt Coire Mhuilidh	233299	864793	233139	863324	0.386	0.818	0.808	54	9	1488	0.44	0.0	1.6	Pelton	159	139	1.6	0.6	0.34	15	0.46	0.12	0.0262	5
Stirling	Allt Innis Daimh	246789	736412	247649	736782	1.061	3.319	0.797	78	18	4166.7	0.45	0.3	1.3	Francis	29.8	27.6	1.1	2.5	4.92	30	13.69	1.87	0.2708	56
Aberdeenshire	Burn of Knock	370071	794616	370241	795216	0.644	2.654	0.793	75	17	3448.2	0.61	1.2	0.9	Francis	20.2	19	0.7	2.5	4.58	40	13.07	3.86	0.6554	241
Highland	Allt Coire Mheadhoin	216277	815637	217919	814769	1.095	2.517	0.789	74	16	3299	0.34	4.9	2.2	Pelton	159	141	2.2	1	0.97	15	1.313	0.14	0.0184	5
Highland	Allt an Amair	209382	768874	207394	769450	3.289	8.031	0.789	85	22	9220.6	0.32	2.4	4.7	Francis	90.3	83.4	3.6	2.5	4.8	15	6.498	0.71	0.0767	34
Perth and Kinross	River Ericht	314662	751670	315525	751508	0.745	3.195	0.787	77	18	4026.1	0.62	0.8	1.4	Francis	23.5	21.5	1.1	2.5	4.58	40	13.61	3.78	0.6193	192
Perth and Kinross	Allt Odhar	273931	747864	273679	746962	0.587	1.038	0.786	59	11	1707.8	0.33	0.2	1.1	Pelton	126	115	1.1	0.8	0.64	15	0.915	0.1	0.014	9
Highland	Allt Coire Ardair	246574	788796	248016	787363	1.301	2.872	0.785	76	17	3676.7	0.32	5.5	2.4	Pelton	171	158	2.4	1.1	1.04	15	1.447	0.12	0.0142	8
Na h-Eileanan an Iar	Abhainn Eadarra	113194	905382	113022	904169	0.593	1.455	0.785	66	13	2155.3	0.42	0.0	1.4	Francis	78.2	70.1	1.4	1.1	1.04	20	1.672	0.35	0.0606	10
Highland	Kinlochewe River	200598	862635	201854	863242	0.585	1.159	0.780	62	12	1833.7	0.36	0.4	1.6	Pelton	147	136	1.6	0.8	0.54	15	0.743	0.11	0.0231	4
Highland	River Runie	213971	902440	213303	901190	0.373	1.610	0.773	68	14	2312.9	0.71	0.6	1.9	Francis	47.7	43.3	1.7	1.3	1.09	50	4.255	1.27	0.297	40
D&G	Murder Hole	243539	581795	242581	580317	2.273	4.707	0.767	82	20	5634.8	0.28	15.6	2.1	Pelton	232	212	2.1	1.1	1.36	10	1.371	0.15	0.0293	8
Highland	Allt na Muidhe	212440	754877	211928	756615	0.898	1.989	0.764	72	15	2713.2	0.35	2.9	2.1	Pelton	159	139	2.1	0.9	0.81	15	1.042	0.1	0.0006	4
Argyll and Bute	Eas nam Broighleag	195834	679796	193936	679206	0.546	1.532	0.761	67	14	2219.5	0.46	0.2	2.8	Pelton	101	89.9	2.3	1	0.76	20	1.383	0.29	0.0647	11
Perth and Kinross	Allt Lairig nan Lunn	244898	740423	245554	741667	0.552	1.234	0.758	63	12	1897.7	0.39	0.0	1.6	Pelton	106	99.1	1.6	1	0.7	20	1.27	0.16	0.0342	6
North Ayrshire	Allt Mar	199205	630966	201054	630646	0.509	1.142	0.750	62	12	1792.4	0.40	0.6	2.5	Pelton	210	181	2.3	0.6	0.35	15	0.481	0.1	0.024	3
East Ayrshire	Glenmuir Water	260743	620679	259661	621546	0.38	1.637	0.750	69	14	2323.8	0.70	0.2	1.9	Francis	50.2	45.7	1.9	1.3	1.04	50	3.922	1.13	0.1833	61
Argyll and Bute	Loch na Ba¨iste	176615	654986	176645	656041	0.269	0.778	0.732	55	10	1388.5	0.59	0.2	1.3	Pelton	80	73.4	1.3	0.8	0.45	30	0.84	0.28	0.0445	12
Highland	Allt Coire Attadale	177253	847942	174645	848743	1.215	3.879	0.731	80	19	4717.6	0.44	8.7	4.0	Pelton	167	145	3.8	1.1	1.05	20	1.7	0.32	0.0529	8
Perth and Kinross	Castlehill Resr	300188	702983	300519	702993	0.449	1.271	0.722	65	13	1909.4	0.49	0.2	0.6	Francis	30.1	29	0.4	1.6	2	30	6.225	0.98	0.1572	63
Highland	River Beauly	248458	849224	249625	850131	0.346	0.763	0.721	55	10	1364	0.45	0.0	1.9	Pelton	171	159	1.7	0.6	0.27	15	0.34	0.1	0.0178	6
Highland	Allt a' Chonais	205234	848940	204623	849166	0.576	1.472	0.719	68	14	2122.9	0.42	0.2	0.8	Francis	46.3	44.1	0.8	1.5	1.64	25	3.345	0.51	0.0553	15
Highland	Loch nam Breac Buidhe	237316	884454	238582	885314	1.586	5.535	0.715	83	21	6484.2	0.47	12.2	1.7	Francis	50.3	47.9	1.7	2.5	4.09	25	8.303	1.94	0.4651	54
Highland	Allt na Cailliche	227244	799914	227629	800359	0.447	0.868	0.713	58	11	1470	0.38	0.6	0.8	Pelton	100	96.7	0.8	0.9	0.57	15	0.783	0.14	0.0247	5

Run-of-River Sites (5% Discount Rate)

County	River	Intake Easting	Intake Northing	Power house Easting	Power house Northing	Power (MW)	Total cost (M£)	NPV (M£)	LEC (£/MWh)	Discounted Payback Period	Energy production (MWh/year)	CF	Line distance (km)	Road distance (km)	Turbine type	Gross Head (m)	Net Head (m)	Penstock Length (km)	Penstock diameter (m)	Qd (m^3s^{-1})	Qd (FDC percentile)	Q10 (m^3s^{-1})	Q50 (m^3s^{-1})	Q90 (m^3s^{-1})	Catchmnet area (km^2)
Highland	River Romesdal	142074	854015	140868	853405	0.515	1.496	0.712	68	14	2143.6	0.48	0.6	1.8	Francis	77.9	71.3	1.6	1.1	0.89	25	1.827	0.4	0.0763	14
Highland	Allt Dearg Mar	146172	828275	147546	829245	0.702	1.700	0.710	70	15	2361.6	0.38	3.6	2.0	Pelton	160	143	1.8	0.8	0.61	15	0.818	0.15	0.0289	4
Highland	Allt Mar	273545	804911	274716	802758	0.582	1.798	0.705	71	15	2462.9	0.48	2.8	3.3	Pelton	183	169	3.0	0.8	0.43	20	0.813	0.18	0.044	10
City of Edinburgh	Torduff Resr	323824	674038	324375	674069	0.338	1.337	0.695	67	13	1960.9	0.66	8.4	0.7	Francis	33.2	31	0.7	1.4	1.41	45	3.806	1.33	0.2218	106
Argyll and Bute	Allt a Mhuilinn	223001	718291	223007	716417	2.618	6.326	0.695	84	21	7318.4	0.32	5.6	2.1	Francis	62.1	56.4	2.1	2.5	5.69	15	7.569	0.92	0.1407	31
Perth and Kinross	Allt Coire a Chearcaill	266359	748693	266519	748022	1.114	2.236	0.694	75	16	2924.5	0.30	5.7	0.8	Pelton	102	99.6	0.8	1.4	1.42	15	2.064	0.11	0.0189	13
Highland	Allt a' Gharbh Bhaid	243153	867909	241475	867990	0.424	0.971	0.677	61	11	1553.6	0.42	0.0	2.0	Pelton	150	137	1.8	0.7	0.38	20	0.705	0.1	0.014	7
Highland	Abhainn Beinn nan Eun	244846	874202	245918	873404	0.759	2.488	0.667	76	17	3175.2	0.48	6.7	4.2	Pelton	101	95.1	1.8	1.2	1.01	20	1.681	0.42	0.0936	17
East Dunbartonshire	Jamie Wright's Well	261851	680465	261008	679464	0.862	2.211	0.666	75	16	2877.4	0.38	7.7	1.7	Pelton	177	167	1.7	0.9	0.64	15	0.918	0.17	0.0332	6
D&G	Euchan Water	272877	606975	276506	608601	1.036	3.754	0.662	81	19	4531.6	0.50	5.6	4.5	Pelton	150	125	4.5	1.1	1.05	25	2.687	0.4	0.084	19
Highland	Allt Achadh nan Sabhal	216157	790997	215277	789571	1.307	3.122	0.659	79	18	3850.2	0.34	10.8	2.0	Pelton	231	222	2.0	1	0.74	15	1.012	0.11	0.0194	4
Highland	Allt Iarairidh	231636	815021	232448	814417	0.395	0.837	0.655	59	11	1393.8	0.40	0.0	1.4	Pelton	116	103	1.2	0.7	0.48	15	0.678	0.14	0.0267	5
Argyll and Bute	Allt Teanga Brideig	156175	731578	156381	730559	0.639	1.387	0.652	68	14	1981.3	0.35	2.0	1.4	Pelton	115	106	1.2	0.9	0.76	15	0.973	0.12	0.0112	3
Highland	Allt Beithe Garbh	206477	821010	207223	819913	1.838	3.941	0.649	81	20	4722.6	0.29	15.3	7.0	Pelton	252	231	1.5	0.9	1	10	1.01	0.1	0.0103	3
D&G	Loch Trool	241572	581286	241669	580240	1.977	4.078	0.649	82	20	4868.9	0.28	15.8	1.2	Pelton	169	162	1.2	1.3	1.55	10	1.559	0.14	0.0189	9
Stirling	Allt a' Bheithe	275002	704821	275680	703964	0.35	1.271	0.647	67	13	1853.2	0.60	0.0	1.7	Francis	54.5	51	1.4	1.2	0.86	35	1.954	0.63	0.1223	22
Highland	Allt Beithe	165613	765430	165695	767449	0.574	1.776	0.646	72	15	2395.3	0.48	2.3	2.6	Pelton	121	106	2.4	0.9	0.68	20	1.101	0.26	0.0473	9
Perth and Kinross	Allt a' Chreagain Odhair	261164	760017	260999	759002	0.429	1.328	0.643	68	14	1911.4	0.51	0.2	1.4	Francis	62.8	56.5	1.4	1.1	0.95	25	1.712	0.49	0.0866	12
North Ayrshire	Glenashdale Falls	201998	625023	203406	625106	0.458	1.047	0.641	64	12	1608.6	0.40	0.8	2.8	Pelton	166	155	1.7	0.7	0.37	15	0.502	0.11	0.0244	4
D&G	Loch of the Lowes	248572	571193	248036	570267	0.942	2.874	0.635	79	18	3565.5	0.43	8.0	1.6	Francis	84.6	76.7	1.6	1.3	1.51	25	3.782	0.48	0.092	25
Highland	River Brora	291104	908460	292012	907481	0.279	0.725	0.631	56	10	1254.9	0.51	0.2	1.6	Pelton	137	125	1.6	0.6	0.27	20	0.417	0.13	0.0217	8
Highland	Allt Coire na Maine	283375	901411	283915	900356	0.258	0.887	0.630	61	11	1428.6	0.63	0.3	1.7	Pelton	77.9	68.8	1.7	0.8	0.46	35	1.096	0.33	0.0491	23
Highland	Allt na Fearna Mar	255218	903763	257137	902063	0.532	2.372	0.630	77	17	3022.1	0.65	0.5	3.4	Francis	78.9	68.6	3.4	1.2	0.96	40	2.595	0.82	0.1788	31
Highland	Am Fa s-allt	196660	812164	197083	814036	1.899	4.226	0.625	82	20	5010.3	0.30	15.7	2.3	Pelton	273	242	2.3	0.9	0.99	10	0.989	0.1	0.0018	2
Highland	Loch a' Gharbh-bhaid Beag	226244	950859	225385	952238	0.346	1.522	0.624	71	15	2105.8	0.69	0.6	1.8	Francis	49.3	43.3	1.8	1.2	1.01	50	4.506	1.13	0.2145	35
North Ayrshire	Garbh Allt	194129	636350	193975	635266	0.394	0.825	0.622	59	11	1356.1	0.39	0.0	1.3	Pelton	130	119	1.3	0.7	0.41	15	0.561	0.11	0.0211	4
Highland	Allt na Cra¬che	176241	750413	174766	750737	0.28	0.902	0.617	61	12	1434.1	0.59	0.0	1.8	Pelton	89.6	81.2	1.8	0.8	0.43	35	1.327	0.26	0.0476	6
Highland	Allt Gleann Chaorachain	210587	883257	211434	885151	0.699	2.108	0.611	75	17	2724.6	0.44	6.8	2.4	Pelton	210	184	2.4	0.7	0.47	15	0.624	0.17	0.0435	5
Highland	Loch na Ba¨iste	238274	841779	238591	841195	0.436	0.813	0.610	59	11	1333.4	0.35	0.0	1.1	Pelton	109	106	0.9	0.9	0.51	15	0.73	0.11	0.0176	5
Highland	Allt na Glaise	239643	936386	239098	934351	0.815	1.896	0.609	74	16	2496.1	0.35	1.6	2.9	Pelton	179	164	2.7	0.9	0.62	15	0.831	0.11	0.0171	3
Perth and Kinross	Black Spout	296719	758481	295049	757532	0.436	1.237	0.602	68	14	1783	0.47	1.8	2.1	Pelton	162	148	2.1	0.7	0.36	15	0.46	0.14	0.0218	11
Highland	River Duror	201719	753768	200355	755021	1.346	3.928	0.601	82	20	4672.7	0.40	12.1	2.1	Pelton	119	108	2.1	1.3	1.59	20	2.642	0.33	0.0301	11
Highland	Loch Fleodach Coire	227296	922753	225781	921858	1.091	3.148	0.600	80	19	3833.6	0.40	11.9	2.1	Pelton	189	170	2.1	0.9	0.81	15	1.064	0.23	0.0487	6
Argyll and Bute	River Ruel	202993	683096	201832	681509	0.381	1.180	0.599	67	13	1719.4	0.51	0.0	2.9	Pelton	150	132	2.9	0.7	0.36	25	0.895	0.16	0.0312	6
Highland	Easan Choineas	240860	944691	243944	941981	0.978	4.747	0.598	83	21	5549.9	0.65	11.2	4.7	Pelton	130	110	4.7	1.2	1.12	35	2.944	0.87	0.2287	18
Highland	River Attadale	194338	837160	194251	837809	0.254	0.542	0.597	51	9	1033.2	0.46	0.0	0.8	Pelton	106	102	0.8	0.7	0.31	20	0.533	0.12	0.0224	4
Argyll and Bute	Croe Water	224431	706167	224030	706007	0.899	1.791	0.596	74	16	2373.2	0.30	5.3	0.5	Pelton	106	100	0.5	1	1.13	10	1.135	0.13	0.0032	3
Highland	Abhainn Bad na h-Achlaise	212601	921360	212287	921460	0.47	1.379	0.593	70	14	1928.6	0.47	2.6	1.2	Francis	44.3	42.7	0.4	1.3	1.39	25	2.801	0.65	0.1285	26
Highland	Allt Bail' an Tuim Bhuidhe	228658	814492	228149	812890	0.318	0.855	0.590	61	12	1363.1	0.49	0.2	2.1	Pelton	160	143	2.1	0.6	0.27	20	0.448	0.12	0.0257	4
Argyll and Bute	Loch Steallaig	196838	746215	195945	744975	0.973	2.554	0.587	78	18	3186.3	0.37	5.0	1.8	Pelton	100	93	1.8	1.3	1.32	20	2.305	0.19	0.0241	12

Run-of-River Sites (5% Discount Rate)

County	River	Intake Easting	Intake Northing	Power house Easting	Power house Northing	Power (MW)	Total cost (M£)	NPV (M£)	LEC (£/MWh)	Discounted Payback Period	Energy production (MWh/year)	CF	Line distance (km)	Road distance (km)	Turbine type	Gross Head (m)	Net Head (m)	Penstock Length (km)	Penstock diameter (m)	Qd (m^3s^{-1})	Qd (FDC percentile)	Q10 (m^3s^{-1})	Q50 (m^3s^{-1})	Q90 (m^3s^{-1})	Catchmnet area (km^2)
Argyll and Bute	Allt Broighleachan	223428	733277	224333	732544	0.98	2.283	0.586	77	17	2894.2	0.34	2.1	2.1	Pelton	100	92.9	1.9	1.3	1.34	15	1.782	0.18	0.0283	9
Highland	Loch Chealamy	272339	948572	272288	948941	0.801	4.297	0.586	83	20	5056.6	0.72	9.7	0.4	Kaplan	10.9	9.37	0.4	3	10.2	50	35.01	11.6	2.291	440
Highland	Allt Coire Eaghainn	220586	832600	220606	831687	0.769	1.561	0.582	72	15	2115.4	0.31	1.9	2.1	Pelton	104	101	1.0	1.2	0.96	15	1.325	0.1	0.013	6
Highland	Alltan Eisg	188428	846487	187657	846386	0.45	0.911	0.581	63	12	1416.4	0.36	0.3	2.6	Pelton	114	108	0.9	0.8	0.52	15	0.685	0.1	0.0168	3
D&G	Bogrie Lane	291227	575201	292854	575572	0.46	1.954	0.580	75	17	2536.5	0.63	1.6	1.9	Francis	56.3	52.9	1.9	1.4	1.08	40	2.74	0.86	0.11	43
Highland	Lochan nam Breac	237279	864329	237199	863600	0.286	0.605	0.575	54	10	1083.6	0.43	0.2	1.0	Pelton	122	113	0.8	0.6	0.31	15	0.404	0.11	0.0198	6
Na h-Eileanan an Iar	Loch an Ruisg	118486	905693	119385	905814	0.25	0.717	0.574	58	11	1203.1	0.55	0.3	1.0	Pelton	73.3	67.8	1.0	0.8	0.46	30	1.101	0.24	0.053	6
Highland	Allt na h-Easaiche	181742	747745	181613	747500	0.32	0.702	0.574	58	11	1187.3	0.42	1.4	0.5	Pelton	87.1	85.3	0.3	0.8	0.47	25	1.032	0.11	0.0197	5
Highland	Caledonian Canal	266057	839520	265692	840838	0.259	0.817	0.569	61	12	1307.2	0.58	0.7	1.6	Pelton	105	96.4	1.6	0.7	0.33	25	0.572	0.2	0.0383	15
Highland	Lochan na Doire-uaine	257433	786668	257503	788430	0.431	1.460	0.568	71	15	1997.2	0.53	1.6	2.8	Pelton	103	91.2	2.3	0.9	0.59	25	1.337	0.28	0.0509	13
North Ayrshire	Allt na h-Airighe	190005	639523	189496	637967	0.502	1.241	0.565	69	14	1758.9	0.40	0.5	3.1	Pelton	130	117	1.8	0.8	0.53	20	0.937	0.11	0.0193	6
North Ayrshire	Allt Tigh an Shiorraim	192193	641518	193436	640345	0.701	1.849	0.561	75	16	2409.5	0.39	4.5	7.0	Pelton	220	203	1.9	0.7	0.43	15	0.586	0.12	0.0252	4
Highland	Allt Coire a' Bha inidh	203714	846780	202997	848407	0.606	1.500	0.556	72	15	2030.1	0.38	0.2	2.0	Pelton	111	106	2.0	1.1	0.72	20	1.226	0.13	0.0076	4
Highland	Loch Aline	168257	746556	168595	746328	0.242	0.475	0.553	50	9	927.48	0.44	0.0	0.5	Pelton	89.9	87.3	0.5	0.7	0.34	15	0.443	0.13	0.0252	4
Stirling	Loch Mahaick	269873	706250	269961	704423	0.331	1.004	0.536	66	13	1483.1	0.51	0.0	2.4	Pelton	130	117	2.2	0.7	0.35	20	0.544	0.16	0.0289	7
Perth and Kinross	Allt Chaldar	247483	758848	246508	756903	0.303	1.169	0.530	69	14	1655.3	0.62	0.4	2.6	Pelton	97.4	84.2	2.6	0.8	0.45	35	1.186	0.3	0.0483	15
Highland	Allt Cha iteag	312963	948726	313901	948944	0.804	3.669	0.528	83	20	4339	0.62	2.5	1.3	Francis	22.6	20.4	1.1	2.6	5.24	40	11.95	4.57	0.9686	231
Stirling	Lossburn Resr	284701	697947	284841	696953	0.45	0.962	0.525	66	13	1429.1	0.36	1.0	1.1	Pelton	124	110	1.1	0.7	0.51	15	0.723	0.1	0.0107	11
Perth and Kinross	Allt Kinardochy	277575	757149	278188	758401	0.335	0.922	0.522	65	13	1384.7	0.47	0.0	1.8	Pelton	102	93	1.8	0.8	0.45	20	0.792	0.17	0.0172	14
Highland	Allt Dearg	205314	849727	204983	849523	0.303	1.036	0.521	67	13	1506.5	0.57	0.0	0.4	Francis	27.9	26.4	0.4	1.4	1.51	40	6.613	1.08	0.1818	40
Argyll and Bute	Newton Bay	205613	696920	204413	697127	0.501	1.196	0.520	70	14	1676.8	0.38	1.0	1.4	Pelton	110	106	1.4	1	0.59	20	1.055	0.11	0.0265	6
Na h-Eileanan an Iar	Lochan Beag	105233	907701	104985	907624	0.381	1.018	0.520	67	13	1486	0.44	0.6	0.3	Francis	36.7	35.5	0.3	1.3	1.37	25	2.608	0.57	0.1029	18
Highland	Culachy Falls	237923	806883	238015	807065	0.537	1.782	0.518	75	17	2305	0.49	1.1	1.3	Francis	20.9	20.7	0.2	2.5	3.48	30	8.706	2.02	0.4518	74
Perth and Kinross	River Tummel	299127	755650	296963	754785	0.47	1.642	0.517	74	16	2154.3	0.52	4.5	2.9	Pelton	226	201	2.9	0.6	0.29	20	0.427	0.13	0.0221	11
Highland	Allt Ca m Ghlinne	224607	753036	224135	753776	0.638	1.418	0.516	72	15	1911.9	0.34	2.0	1.4	Pelton	109	105	1.2	1.1	0.76	15	0.986	0.11	0.0019	4
Highland	Allt na Maine	170642	854187	169452	856473	1.113	3.768	0.513	83	20	4433.8	0.45	14.1	3.4	Pelton	224	203	3.2	0.9	0.69	15	0.894	0.27	0.0635	7
Argyll and Bute	Acharossan Burn	195867	677177	194089	677040	0.391	1.115	0.511	69	14	1583.5	0.46	1.0	2.3	Pelton	151	139	2.1	0.7	0.35	20	0.642	0.13	0.0305	4
Stirling	River Balvag	253670	719423	253727	720300	0.486	1.653	0.509	75	16	2159.9	0.51	2.4	1.0	Francis	52.3	50	1.0	1.4	1.21	35	4.9	0.56	0.0891	30
Highland	Loch Sunart	177669	758783	177805	759582	0.285	0.652	0.508	59	11	1084	0.43	0.3	0.9	Pelton	101	94.8	0.9	0.7	0.37	20	0.624	0.12	0.0207	3
Highland	Allt a' Ghlinne	237308	857926	238608	857566	0.402	1.065	0.508	68	14	1526.9	0.43	0.5	1.6	Pelton	100	94.2	1.6	0.9	0.53	20	0.994	0.17	0.0229	11
Perth and Kinross	Allt a' Chrombaidh	279259	767244	278911	766545	0.34	0.889	0.508	65	13	1337.8	0.45	1.8	0.9	Pelton	102	98.1	0.9	0.8	0.43	15	0.541	0.16	0.0265	10
Highland	Allt Tarsuinn Mar	258483	797466	257857	793954	0.938	3.727	0.507	83	20	4385.7	0.53	6.8	4.5	Pelton	139	116	4.3	1.1	1.02	25	2.229	0.5	0.122	16
Highland	Allt Garbh	139491	847735	140788	848978	0.319	1.103	0.507	69	14	1567.3	0.56	0.3	2.5	Pelton	108	98.4	2.5	0.8	0.4	25	0.677	0.23	0.0551	6
Highland	Allt na Fuar-ghlaic	274032	838921	272639	839386	0.3	0.991	0.502	67	13	1442.7	0.55	0.0	2.0	Pelton	88.1	75.7	2.0	0.8	0.49	20	0.735	0.25	0.0524	15
Argyll and Bute	Allt Ghamhnain	228647	735436	227780	736803	0.595	1.466	0.500	73	16	1952.1	0.37	0.2	2.1	Pelton	110	105	1.9	1.1	0.71	20	1.221	0.12	0.0057	5
Highland	River Hinnisdal	140741	857921	139322	857112	0.435	1.714	0.499	75	17	2217.4	0.58	0.5	2.2	Francis	52.4	47.1	1.8	1.3	1.16	35	3.137	0.8	0.1646	26
Argyll and Bute	Allt an t-Sagairt	153249	673366	154395	672287	0.542	1.468	0.492	74	16	1948	0.41	0.0	2.4	Pelton	101	90.1	2.2	1	0.75	20	1.266	0.17	0.0268	9
Stirling	Allt a' Choin	241529	712652	240705	711963	1.932	3.999	0.487	84	21	4663.1	0.28	16.3	1.2	Pelton	192	181	1.2	1.1	1.36	10	1.364	0.12	0.0162	6
Argyll and Bute	Eas nam Broighleag	194583	683534	193531	684201	0.257	0.735	0.486	62	12	1155.4	0.51	0.3	1.7	Pelton	121	107	1.5	0.6	0.3	20	0.543	0.14	0.0317	4
Highland	An Leth-allt	170180	795715	169985	794882	0.494	1.144	0.485	70	14	1594.7	0.37	1.6	2.7	Pelton	121	113	1.1	0.8	0.54	15	0.712	0.12	0.0193	4

Run-of-River Sites (5% Discount Rate)

County	River	Intake Easting	Intake Northing	Power house Easting	Power house Northing	Power (MW)	Total cost (M£)	NPV (M£)	LEC (£/MWh)	Discounted Payback Period	Energy production (MWh/year)	CF	Line distance (km)	Road distance (km)	Turbine type	Gross Head (m)	Net Head (m)	Penstock Length (km)	Penstock diameter (m)	Qd (m^3s^{-1})	Qd (FDC percentile)	Q10 (m^3s^{-1})	Q50 (m^3s^{-1})	Q90 (m^3s^{-1})	Catchmnet area (km^2)
Highland	Allt na Graidhe	232729	805540	234092	805789	0.228	0.887	0.484	66	13	1317.9	0.66	0.4	1.9	Pelton	68.9	59.5	1.7	0.8	0.48	40	1.538	0.39	0.0787	14
North Lanarkshire	East Corrie Resr	271018	679633	271988	678111	0.315	0.926	0.480	67	13	1356.9	0.49	0.6	2.3	Pelton	166	150	2.3	0.6	0.26	20	0.483	0.11	0.0185	5
Highland	Allt na Lairige	228849	771673	230728	769523	1.659	5.116	0.478	85	22	5855.2	0.40	13.1	8.6	Pelton	160	143	3.5	1.3	1.47	20	2.492	0.33	0.046	12
Argyll and Bute	Allt nan Nathair	182896	681876	184264	681304	0.297	0.937	0.475	67	13	1365.6	0.53	0.4	1.9	Pelton	110	104	1.9	0.8	0.35	25	0.846	0.17	0.035	7
Highland	Allt Dearg	205567	850200	205441	849972	0.41	1.229	0.472	72	15	1675.5	0.47	0.0	1.6	Francis	26.5	25.5	0.3	1.6	2.1	30	5.785	0.97	0.1674	36
Highland	Allt a' Choire Chaoil	200361	821345	198351	822364	1.639	3.770	0.468	84	21	4402.6	0.31	10.7	3.8	Pelton	253	219	2.7	0.9	0.94	10	0.943	0.11	0.0027	3
Argyll and Bute	Allt Dhoira¨ann	215345	735798	214579	736157	0.97	2.026	0.466	78	18	2528.2	0.30	5.3	1.2	Pelton	122	113	1.0	1	1.09	10	1.089	0.11	0.002	3
North Ayrshire	Allt nan Calaman	195175	634356	194438	635046	0.341	0.793	0.466	64	13	1204	0.40	0.3	1.1	Pelton	104	98.6	1.1	0.8	0.43	20	0.749	0.1	0.0216	4
Highland	Allt Fhaolain	214875	752408	215816	750606	1.468	3.249	0.460	83	20	3836.4	0.30	8.8	2.2	Pelton	200	181	2.2	1	1.02	10	1.024	0.1	0.0006	3
Highland	Allt a' Chalda Mar	226259	923950	225303	923433	1.244	2.948	0.457	82	20	3511.6	0.32	12.6	2.1	Pelton	239	223	1.3	0.8	0.7	10	0.712	0.13	0.0255	4
Highland	Loch an Inneil	222457	937340	221410	936417	0.719	2.579	0.455	81	19	3113.2	0.49	9.0	2.7	Pelton	111	107	1.7	1.2	0.85	20	1.368	0.39	0.0901	13
Argyll and Bute	Crarae Bay	197907	697976	198563	697369	0.331	0.816	0.454	65	13	1219	0.42	0.4	1.4	Pelton	100	94.7	1.2	0.8	0.43	20	0.79	0.13	0.0283	4
Highland	Allt na Doire-giubhais	208884	863813	208633	864415	0.473	1.365	0.452	74	16	1806.6	0.44	4.5	1.3	Pelton	153	142	1.3	0.7	0.41	15	0.534	0.15	0.0362	4
Argyll and Bute	Allt Robuic	209523	696277	210676	696633	0.789	1.902	0.446	78	18	2379.4	0.34	4.1	1.7	Pelton	143	129	1.7	0.9	0.77	15	1.068	0.13	0.0319	5
Na h-Eileanan an Iar	Loch Mhisteam	115864	909206	117813	909454	0.634	1.693	0.446	77	17	2154.3	0.39	1.9	3.1	Pelton	164	144	2.6	0.8	0.55	15	0.711	0.13	0.017	4
Highland	Fa¨ith Raoicidhdail	195159	761278	195880	760806	0.249	0.615	0.445	60	11	996.78	0.46	0.0	1.0	Pelton	86.2	78.9	1.0	0.7	0.39	30	1.103	0.11	0.0112	5
Highland	Lochan na Creige Duibhe	174372	784866	173936	784391	0.243	0.603	0.443	60	11	982.49	0.46	0.0	1.0	Pelton	70.8	67.2	0.7	0.8	0.45	30	1.255	0.13	0.0133	7
Na h-Eileanan an Iar	Loch na Sgeireagan Mar	114226	904096	113608	903634	0.254	0.599	0.441	60	11	975.74	0.44	0.2	0.9	Pelton	98.5	93.6	0.9	0.7	0.33	20	0.54	0.11	0.0197	3
Argyll and Bute	Allt Coire Bhiocair	224566	736157	225899	735314	0.559	1.369	0.438	74	16	1800.4	0.37	0.3	2.0	Pelton	102	93.3	1.8	1	0.75	20	1.35	0.1	0.0185	4
Highland	Allt Beithe	189089	887853	188448	888465	0.231	0.711	0.436	64	12	1092.7	0.54	0.3	1.4	Pelton	71.7	66.8	1.1	0.8	0.43	25	0.746	0.22	0.046	11
Stirling	River Balvag	256888	723148	258066	722036	0.621	1.508	0.435	76	17	1948.5	0.36	0.6	1.8	Pelton	109	104	1.8	1.1	0.75	20	1.454	0.1	0.0151	9
Highland	Allt an Eain	225220	810498	225019	811401	0.27	0.627	0.431	61	12	999.09	0.42	0.0	1.0	Pelton	102	95.4	1.0	0.7	0.35	20	0.674	0.1	0.02	3
Highland	Allt an Ruighe Dhuibh	223553	826557	224391	826290	0.807	1.911	0.431	78	18	2377.9	0.34	5.1	1.0	Pelton	101	97.2	1.0	1.2	1.05	15	1.471	0.17	0.031	9
Highland	Lochan Kilmallie	211995	779891	213198	779149	0.342	1.088	0.426	71	15	1490.8	0.50	1.6	1.6	Pelton	98.3	88.9	1.6	0.8	0.48	25	1.124	0.2	0.036	7
Perth and Kinross	Falls of Keltie	285919	725525	286716	724513	0.496	1.305	0.423	74	16	1721.1	0.40	2.5	1.9	Pelton	169	154	1.9	0.7	0.4	15	0.563	0.11	0.0195	5
Argyll and Bute	Allt Glinne Mhair	220463	706240	219050	704421	0.77	2.118	0.421	80	19	2592.5	0.38	0.0	2.7	Pelton	100	89.7	2.7	1.2	1.08	20	1.822	0.16	0.0047	7
Highland	Allt Fionndrigh	265783	802378	268222	799194	0.58	2.124	0.420	80	19	2597.7	0.51	2.9	4.7	Pelton	229	201	4.4	0.7	0.36	25	0.827	0.16	0.0374	7
Perth and Kinross	Burn of Auchrannie	329117	754307	330460	752931	0.741	3.193	0.419	83	20	3745.3	0.58	8.6	3.0	Francis	91.1	78.8	2.8	1.2	1.16	30	2.71	0.71	0.1026	73
Highland	Allt a' Chaorainn	269083	801224	269254	799512	0.488	1.566	0.405	77	17	1987.4	0.46	2.9	1.9	Pelton	110	105	1.9	1	0.58	20	1.074	0.23	0.055	11
Highland	River Beauly	246946	844801	247647	844200	0.204	0.688	0.405	64	13	1044.1	0.58	0.3	1.1	Pelton	62.3	57	1.1	0.8	0.44	30	1.003	0.26	0.0389	15
D&G	Big Water of Fleet	255892	562907	257258	561186	0.404	1.960	0.403	79	19	2409.2	0.68	0.2	2.6	Francis	58.1	52.8	2.6	1.3	0.96	45	4.169	0.92	0.1756	32
Highland	Allt a' Choire Dhuibh	193018	789018	193529	790092	1.268	2.816	0.401	83	20	3326.7	0.30	10.0	3.0	Pelton	193	177	1.4	0.9	0.9	10	0.899	0.1	0.0019	2
Highland	Kyle of Sutherland	249190	897523	250442	898806	0.699	2.357	0.398	81	19	2831.4	0.46	7.6	2.4	Pelton	129	112	2.0	0.9	0.78	15	0.993	0.29	0.0536	15
Highland	Loch Catrina	271008	876368	271746	875800	0.171	0.767	0.396	67	13	1122.6	0.75	0.5	1.3	Pelton	50.8	47.1	1.3	0.9	0.45	55	1.882	0.58	0.1004	41
Highland	An t-Sa¹ileag	201856	781813	202140	778903	0.705	2.370	0.395	81	19	2843.3	0.46	0.2	3.4	Pelton	101	90	3.4	1.2	0.99	30	2.987	0.27	0.0304	12
Argyll and Bute	Loch nan Ca¨ard Beag	191760	702886	190155	704164	0.921	2.418	0.395	81	20	2895.3	0.36	6.9	2.5	Pelton	216	194	2.5	0.8	0.59	15	0.817	0.12	0.028	4
Argyll and Bute	Lochan Laraiche	178199	684744	177492	685834	0.912	2.400	0.395	81	20	2875.1	0.36	5.5	2.1	Pelton	144	130	2.1	1	0.88	15	1.18	0.17	0.0319	9
Stirling	Allt Challum	240171	733292	241435	733648	1.012	2.431	0.391	82	20	2905.5	0.33	5.9	2.3	Pelton	125	116	1.5	1.1	1.1	15	1.492	0.1	0.0056	3
Highland	Loch Meall nan Dearcag	218543	905330	217367	905554	0.257	0.763	0.388	67	13	1112.6	0.50	0.8	1.5	Pelton	105	98.3	1.3	0.7	0.32	20	0.509	0.15	0.0357	4
Perth and Kinross	Black Water	314629	756614	313893	756502	0.233	0.632	0.382	64	12	967.29	0.47	0.6	0.8	Pelton	80.8	74.7	0.8	0.7	0.39	15	0.483	0.16	0.0259	11

Run-of-River Sites (5% Discount Rate)

County	River	Intake Easting	Intake Northing	Power house Easting	Power house Northing	Power (MW)	Total cost (M£)	NPV (M£)	LEC (£/MWh)	Discounted Payback Period	Energy production (MWh/year)	CF	Line distance (km)	Road distance (km)	Turbine type	Gross Head (m)	Net Head (m)	Penstock Length (km)	Penstock diameter (m)	Qd (m^3s^{-1})	Qd (FDC percentile)	Q10 (m^3s^{-1})	Q50 (m^3s^{-1})	Q90 (m^3s^{-1})	Catchmnet area (km^2)
Highland	Allt Mhartuin	215569	854685	214939	855694	0.234	0.916	0.379	70	15	1269.3	0.62	0.4	2.2	Pelton	71.4	61.8	1.7	0.8	0.47	35	1.347	0.32	0.0657	11
Highland	Allt an Daimh	198921	827734	197997	827278	0.668	1.673	0.378	78	18	2082.2	0.36	5.5	1.2	Pelton	160	150	1.2	0.8	0.55	15	0.751	0.11	0.0189	3
Argyll and Bute	Ledmore River	151689	746521	152203	745603	0.313	1.208	0.378	74	16	1582.5	0.58	0.0	1.5	Francis	44.1	40.2	1.2	1.2	0.99	35	2.456	0.69	0.1345	18
Argyll and Bute	Dearg Allt	183680	679292	184833	679226	0.249	0.702	0.373	66	13	1035.2	0.47	0.2	1.3	Pelton	88.6	79.2	1.3	0.7	0.39	25	0.887	0.13	0.0279	6
Highland	Lochan nan Slochd	174255	838937	171477	838544	1.373	4.889	0.362	86	22	5523.9	0.46	17.1	4.0	Pelton	216	188	4.0	1	0.92	15	1.213	0.36	0.0893	11
Glasgow City	White Cart Water	257884	656992	258098	657260	0.525	2.000	0.360	81	19	2420.2	0.53	2.7	0.6	Francis	23.2	22.9	0.4	2.5	3.03	30	5.81	1.89	0.2833	86
Highland	Loch Gynack	275084	802532	275771	800396	0.3	1.228	0.360	75	17	1590.2	0.60	0.3	2.8	Pelton	93.5	76.5	2.8	0.8	0.49	30	1.282	0.3	0.0643	17
Highland	Loch Sgurr na Gaoithe	168311	786546	168033	785930	0.196	0.493	0.356	60	11	797.72	0.46	0.2	1.0	Pelton	94.4	88.5	0.8	0.6	0.27	20	0.462	0.1	0.0203	3
Highland	Allt Coire nan Saobhaidh	218279	797545	219498	800018	0.61	1.761	0.355	80	19	2159.9	0.40	0.8	4.0	Pelton	181	162	3.5	0.8	0.47	20	0.872	0.11	0.018	4
Highland	Dunbeath Water	312758	932241	315524	930416	0.508	2.856	0.354	84	21	3333.7	0.75	0.8	4.7	Francis	81.6	69.4	4.5	1.2	0.91	55	3.138	1.18	0.2423	62
D&G	Kello Water	268694	609042	271072	608841	0.542	1.966	0.352	81	19	2377.7	0.50	2.7	3.5	Pelton	102	88.4	2.7	1	0.77	25	1.954	0.31	0.0629	9
Highland	River Elchaig	197763	827344	197185	827714	1.068	3.765	0.352	85	22	4309.2	0.46	4.8	1.1	Francis	27.3	24.9	0.9	2.5	5.55	30	14.5	2.38	0.3695	70
Highland	Allt Coire na Faochaige	220426	840650	220158	840203	0.215	0.571	0.346	64	12	874	0.46	0.4	0.6	Pelton	65.6	63	0.6	0.8	0.42	30	1.304	0.13	0.0134	7
Highland	Loch Odhar	224870	871066	227167	873864	0.767	2.709	0.345	83	21	3169.7	0.47	0.8	4.9	Pelton	139	113	4.3	1	0.85	25	1.847	0.28	0.0462	10
Highland	Abhainn Ceann-loch-morair	188277	792271	186886	791399	1.735	3.997	0.342	86	22	4551	0.30	9.6	16.5	Pelton	153	137	1.8	1.2	1.61	10	1.607	0.16	0.0042	6
Highland	Loch an Fheair	240833	854249	242649	855075	0.272	0.849	0.341	71	15	1169.8	0.49	0.4	2.2	Pelton	152	139	2.2	0.6	0.24	20	0.392	0.1	0.0183	4
Aberdeenshire	River Dee	382761	802735	382661	802142	0.269	1.067	0.340	74	16	1402.6	0.60	0.0	0.8	Francis	32.2	29.9	0.8	1.3	1.17	35	2.526	0.88	0.1709	87
Perth and Kinross	Allt an Tuim Bhric	264967	737402	265679	737042	0.245	0.730	0.339	68	14	1040.7	0.48	0.8	1.8	Pelton	83.5	75.6	1.0	0.7	0.4	30	1.331	0.13	0.017	9
Argyll and Bute	Loch Breacam	180898	651819	182842	651546	0.224	0.809	0.334	70	15	1120.4	0.57	0.0	2.4	Pelton	120	103	2.2	0.6	0.27	25	0.485	0.15	0.0249	6
Highland	Loch an Alltain-bheithe	232319	860786	232589	861640	0.29	0.876	0.327	72	15	1187.3	0.47	1.3	2.3	Pelton	110	107	1.1	0.8	0.33	20	0.564	0.13	0.0236	6
Argyll and Bute	Bardaravine River	185772	664556	183787	664726	0.299	0.936	0.326	73	16	1251	0.48	0.2	2.5	Pelton	149	127	2.5	0.6	0.29	20	0.518	0.11	0.0215	4
Argyll and Bute	Allt Coire Achaladair	232568	743426	232456	744248	0.231	0.633	0.319	67	13	920.71	0.46	0.2	1.4	Pelton	80.7	73.6	1.0	0.7	0.39	30	1.127	0.1	0.0056	4
Highland	Garbh Allt	273105	903224	272607	901971	0.209	0.986	0.317	74	16	1298.4	0.71	0.0	2.3	Pelton	70.1	58.6	2.3	0.8	0.44	45	1.228	0.43	0.0764	21
Perth and Kinross	Allt a' Chreagain Odhair	261919	761491	261195	759269	0.273	0.929	0.316	73	16	1236.4	0.52	0.0	2.8	Pelton	139	116	2.6	0.6	0.29	20	0.452	0.13	0.0233	6
Argyll and Bute	River Kinglass	213623	735029	213446	735600	0.715	1.541	0.316	79	19	1893.5	0.30	4.3	0.9	Pelton	108	101	0.7	0.9	0.89	10	0.891	0.11	0.0031	3
Highland	Abhainn a' Choire	236188	924507	237431	924762	0.212	0.657	0.312	68	14	941.36	0.51	0.0	1.4	Pelton	86.8	79.4	1.4	0.7	0.33	20	0.529	0.16	0.0407	4
North Ayrshire	Allt na h-Airighe	188945	638557	188705	637596	0.192	0.555	0.307	65	13	827.03	0.49	0.3	1.4	Pelton	102	95.3	1.1	0.6	0.25	20	0.417	0.11	0.0189	4
Highland	Allt a' Ghoirtein-eorna	162735	766652	163205	767709	0.533	1.480	0.306	79	18	1820	0.39	4.6	1.6	Pelton	171	158	1.6	0.7	0.42	15	0.557	0.11	0.0184	4
Argyll and Bute	Little Eachaig River	212323	681421	213117	681342	0.512	1.416	0.304	79	18	1750.4	0.39	0.4	0.9	Francis	49.4	46.9	0.9	1.4	1.37	25	3.057	0.28	0.0296	16
Renfrewshire	River Gryfe	238437	665812	238938	665612	0.513	2.181	0.301	83	20	2569.7	0.57	0.6	0.7	Francis	22	21.4	0.7	2.5	3.19	35	7.789	2.36	0.3993	81
Argyll and Bute	Coladoir River	157862	729808	156515	730318	0.475	1.809	0.297	81	20	2166.8	0.52	2.1	2.0	Francis	60.1	53.6	1.6	1.2	1.11	35	3.405	0.57	0.0888	15
Highland	Allt a' Choire Bhuidhe	183365	780768	183525	781608	0.234	0.654	0.297	69	14	925.82	0.45	0.4	1.2	Pelton	81.2	73.9	1.0	0.7	0.39	30	1.084	0.1	0.0032	4
Stirling	North Third Resr	273540	692332	275220	692893	0.479	1.559	0.295	80	19	1897.1	0.45	4.6	2.2	Pelton	180	167	2.2	0.7	0.35	15	0.456	0.13	0.0192	5
Argyll and Bute	Abhainn Fionain	197355	717667	199254	717448	0.65	2.394	0.292	84	21	2791.1	0.49	5.4	2.7	Pelton	100	89.6	2.5	1.1	0.91	25	2.228	0.35	0.0773	13
South Lanarkshire	Kype Water	271660	643200	271433	643557	0.272	1.017	0.291	76	17	1312.1	0.55	1.6	0.8	Francis	40.4	38.3	0.5	1.1	0.91	30	1.741	0.56	0.0841	27
Aberdeenshire	Loch Ullachie	337890	799461	338749	797626	0.241	0.871	0.290	74	16	1154	0.55	0.0	2.5	Pelton	109	98.5	2.3	0.7	0.3	25	0.641	0.15	0.024	14
Argyll and Bute	Allt Dobhrain	183186	720654	182779	721004	0.279	1.205	0.288	78	18	1511.9	0.62	0.6	0.8	Francis	29.9	27.9	0.8	1.4	1.3	45	8.457	1.1	0.1853	56
Highland	Allt Coire an t-Seilich	255446	839670	255906	842677	0.471	1.871	0.283	82	20	2223.3	0.54	3.7	3.9	Pelton	172	142	3.7	0.7	0.41	20	0.632	0.2	0.0381	13
Highland	Allt Garbh-Dhoire	220597	807291	220566	808056	0.185	0.510	0.277	66	13	757.11	0.47	0.2	1.1	Pelton	90.5	83.5	0.9	0.6	0.27	20	0.513	0.11	0.0227	4
Highland	An Crom-allt	204489	830876	204326	829449	1.077	2.837	0.276	85	22	3254.8	0.35	10.3	1.8	Pelton	178	168	1.8	1	0.8	15	1.066	0.13	0.0141	4

Run-of-River Sites (5% Discount Rate)

County	River	Intake Easting	Intake Northing	Power house Easting	Power house Northing	Power (MW)	Total cost (M£)	NPV (M£)	LEC (£/MWh)	Discounted Payback Period	Energy production (MWh/year)	CF	Line distance (km)	Road distance (km)	Turbine type	Gross Head (m)	Net Head (m)	Penstock Length (km)	Penstock diameter (m)	Qd (m^3s^{-1})	Qd (FDC percentile)	Q10 (m^3s^{-1})	Q50 (m^3s^{-1})	Q90 (m^3s^{-1})	Catchmnet area (km^2)
Highland	Allt Ceitlein	216982	746631	214803	747740	1.501	4.078	0.272	87	23	4585.6	0.35	11.6	2.8	Pelton	170	157	2.8	1.2	1.21	15	1.579	0.18	0.0059	4
Highland	Allt Leacach	227770	954386	227216	953950	0.182	0.753	0.271	73	15	1013.8	0.64	1.6	0.8	Pelton	51.3	49	0.8	0.9	0.46	35	1.02	0.37	0.1038	11
Argyll and Bute	Loch Fyne	195256	686079	194478	686486	0.235	0.856	0.271	74	16	1124.2	0.55	2.0	1.1	Pelton	79.3	70.3	1.1	0.7	0.41	25	0.977	0.22	0.0531	4
Perth and Kinross	Allt a' Chilleine	271289	738752	269887	739190	1.275	3.256	0.269	86	22	3700.2	0.33	8.8	2.0	Pelton	119	105	1.8	1.2	1.55	15	2.254	0.22	0.0294	20
Highland	River Chracaig	148985	845538	148665	843857	0.316	1.113	0.268	78	18	1397.3	0.50	1.1	2.0	Pelton	95.8	84.9	2.0	0.8	0.46	20	0.733	0.21	0.0439	7
Highland	Allt an Doire Fhea rna	217404	801953	217569	801440	0.181	0.490	0.263	66	13	724.67	0.46	0.2	0.8	Pelton	70.1	66.9	0.6	0.7	0.33	20	0.576	0.12	0.0218	5
Highland	Allt Dearg	138575	849379	139155	850240	0.162	0.657	0.260	71	15	901.73	0.64	0.0	2.1	Pelton	50.9	45.1	1.2	0.8	0.44	35	0.997	0.33	0.0753	9
Highland	Loch Laraig	185061	878657	186591	879201	0.231	0.822	0.260	74	16	1079.4	0.53	0.2	2.1	Pelton	112	104	2.1	0.7	0.27	25	0.528	0.14	0.0272	5
Highland	Allt a' Choire	164075	821416	164875	823271	0.277	1.052	0.258	78	18	1324.6	0.55	0.4	2.3	Pelton	89.1	78.2	2.3	0.8	0.44	25	0.829	0.23	0.0481	5
Highland	Lettie River or Abhainn Deataidh	268270	905650	269659	903926	0.245	1.217	0.256	79	18	1500.2	0.70	0.4	2.5	Pelton	70	61.4	2.5	0.9	0.5	45	1.437	0.47	0.0775	27
Highland	Abhainn Ceann Loch Ainort	153019	826259	153523	826703	0.239	0.671	0.256	72	15	913.51	0.44	0.8	0.7	Pelton	69.4	65.8	0.7	0.8	0.45	25	0.95	0.12	0.0114	4
Highland	Varragill River	147865	838439	147807	839783	0.27	1.365	0.254	80	19	1657.9	0.70	0.2	1.4	Francis	36.5	33	1.4	1.3	1.05	50	3.778	1.2	0.2497	31
Highland	Lochan Tain Mhic Dhughaill	184912	788145	185171	789575	1.502	3.394	0.254	86	22	3836.5	0.29	7.6	15.9	Pelton	194	176	1.9	1	1.08	10	1.083	0.1	0.0103	5
North Ayrshire	Caaf Wafer	228135	648159	228412	648639	0.269	1.033	0.251	78	18	1299.2	0.55	1.1	0.6	Francis	37.7	35.8	0.6	1.2	0.96	30	1.946	0.6	0.0894	27
Scottish Borders	Jed Water	365712	616775	365393	617068	0.308	1.489	0.251	81	19	1788.5	0.66	3.3	0.7	Francis	27.1	25.8	0.5	1.5	1.57	45	4.495	1.49	0.2342	113
Moray	River Spey	332563	851712	332169	851743	0.145	0.566	0.248	69	14	794.81	0.63	0.3	0.4	Kaplan	40	37.5	0.4	0.8	0.47	35	1.057	0.36	0.0622	32
Highland	Allt Coire Chairbe	231569	845900	231379	847162	0.89	2.357	0.248	85	21	2718.1	0.35	7.6	7.1	Pelton	173	164	1.4	0.9	0.68	15	0.957	0.13	0.0236	7
Highland	Allt Eas Mar Cha¹l an Da¹in	181842	815775	181905	817201	1.511	3.606	0.248	87	23	4059.5	0.31	16.4	1.8	Pelton	313	295	1.8	0.8	0.64	10	0.649	0.1	0.0159	4
West Lothian	Linhouse Water	307737	665541	307360	666175	0.221	0.921	0.244	77	17	1173.5	0.61	0.2	1.0	Francis	37.4	34.5	0.8	1.1	0.82	35	1.753	0.63	0.1189	40
North Ayrshire	Haylie Resr	222493	656890	221584	656572	0.201	0.612	0.243	71	15	840.64	0.48	0.8	1.1	Pelton	101	93.3	1.1	0.6	0.26	20	0.485	0.11	0.0167	5
Highland	River Snizort	142068	845958	142653	847563	1.097	4.327	0.242	87	23	4829.9	0.50	0.6	2.0	Francis	40.2	37.9	2.0	2.5	3.63	25	6.139	1.98	0.4195	51
East Ayrshire	Glen Water	257158	640143	257150	638902	0.36	1.596	0.241	82	20	1896.6	0.60	2.0	1.7	Francis	57	53	1.7	1.2	0.85	35	1.819	0.62	0.1038	26
Highland	Abhainn Dhubh	143126	862204	142336	862854	0.288	0.882	0.240	76	17	1128.3	0.45	1.8	1.4	Pelton	95.2	85.9	1.1	0.7	0.42	20	0.707	0.14	0.0252	4
Argyll and Bute	Allt Bhreacnais	228517	743598	228426	742786	0.245	1.072	0.239	79	18	1332.3	0.62	3.5	1.1	Pelton	73.1	67.8	1.1	0.8	0.45	35	1.82	0.31	0.0696	9
Stirling	Duchray Water	240145	700143	241870	700582	1.129	3.160	0.235	86	22	3571.4	0.36	11.5	2.5	Pelton	188	167	2.1	0.9	0.85	15	1.159	0.17	0.0363	7
Highland	Lochan Dubh na Ba¨iste	225223	886849	225595	888022	0.69	2.052	0.233	84	21	2379.3	0.39	7.5	7.5	Pelton	208	195	1.4	0.7	0.44	15	0.596	0.13	0.0287	3
Highland	Abhainn Droma	219634	878720	219407	879106	0.201	0.938	0.232	77	18	1181.8	0.67	0.0	0.5	Francis	22.4	21.2	0.5	1.4	1.29	50	6.202	1.48	0.3194	46
Perth and Kinross	Loch na Ba	288014	753458	288870	751825	0.614	1.831	0.228	84	21	2138.2	0.40	6.0	2.0	Pelton	210	195	2.0	0.7	0.39	15	0.555	0.11	0.0155	8
Highland	Loch Airighe Bheg	271200	904475	271303	903997	0.155	0.544	0.227	70	15	754.97	0.56	0.7	0.6	Pelton	53	50.8	0.6	0.8	0.38	25	0.627	0.22	0.0387	12
Highland	Allt Dogha	208472	778248	208190	777207	0.226	0.665	0.226	73	16	885.43	0.45	0.0	1.4	Pelton	80.5	71.1	1.2	0.7	0.39	25	0.965	0.11	0.0245	5
Perth and Kinross	Burn of Drimmie	317106	750957	316891	750442	0.171	0.562	0.226	71	15	773.99	0.52	1.2	0.9	Pelton	82	76.9	0.7	0.6	0.27	20	0.394	0.13	0.0205	8
Highland	Abhainn Osgaig	205572	911391	205381	911603	0.303	1.177	0.220	80	19	1429.9	0.54	0.8	0.3	Francis	22.9	22	0.3	1.6	1.84	35	4.961	1.24	0.2504	44
Fife	Cameron Reservoir	341704	713809	341413	714478	0.286	1.139	0.218	80	19	1387.5	0.55	2.0	0.8	Francis	46.4	43.6	0.8	1.1	0.83	30	1.575	0.51	0.0615	58
Argyll and Bute	Allt Gleann Bhisdeal	145216	667506	144253	667266	0.238	0.854	0.218	77	17	1081.5	0.52	1.4	1.1	Pelton	69.1	62.8	1.1	0.8	0.47	25	0.997	0.21	0.0326	6
Argyll and Bute	Allt na Coille Maire	150968	729982	151168	729602	0.175	0.447	0.216	68	14	642.78	0.42	0.0	0.7	Pelton	61.4	58.2	0.5	0.7	0.37	20	0.631	0.1	0.0227	4
Highland	Bay of Swordly	274131	961881	273739	962552	0.182	0.627	0.216	73	16	835.79	0.52	0.8	1.2	Pelton	75.7	71	1.0	0.7	0.32	20	0.45	0.16	0.0294	9
Highland	Allt na Criche	196271	781047	196025	779531	0.388	1.635	0.215	83	20	1918.3	0.57	0.0	1.9	Francis	49.2	44.2	1.9	1.3	1.1	45	6.712	0.84	0.0503	25
Highland	Loch Maine Sheilg	192738	889405	193239	890696	0.574	1.992	0.215	84	21	2301.5	0.46	6.0	2.0	Pelton	101	92.6	1.7	1	0.78	15	0.982	0.3	0.0694	11
Argyll and Bute	Abhainn Loch Fhuaran	158389	728009	158515	728846	0.456	1.292	0.211	81	20	1547.1	0.39	3.8	1.4	Pelton	106	102	0.9	0.9	0.56	15	0.722	0.15	0.0276	3
Highland	Allt an t-Sluichd	193858	765618	194170	764666	0.756	1.936	0.204	85	21	2233.9	0.34	4.0	5.6	Pelton	109	106	1.2	1.2	0.89	15	1.189	0.12	0.0122	5

Run-of-River Sites (5% Discount Rate)

County	River	Intake Easting	Intake Northing	Power house Easting	Power house Northing	Power (MW)	Total cost (M£)	NPV (M£)	LEC (£/MWh)	Discounted Payback Period	Energy production (MWh/year)	CF	Line distance (km)	Road distance (km)	Turbine type	Gross Head (m)	Net Head (m)	Penstock Length (km)	Penstock diameter (m)	Qd (m^3s^{-1})	Qd (FDC percentile)	Q10 (m^3s^{-1})	Q50 (m^3s^{-1})	Q90 (m^3s^{-1})	Catchmnet area (km^2)
D&G	East Channel	248765	558820	247509	558450	0.253	0.962	0.202	79	18	1186.2	0.54	1.3	1.5	Pelton	75.9	67.7	1.5	0.8	0.46	20	0.757	0.23	0.0394	10
Highland	Allt Coire na Cloiche	256251	880285	256280	878192	0.617	2.534	0.202	86	22	2873.6	0.53	6.1	2.7	Francis	89.9	77.9	2.5	1.1	0.98	25	1.749	0.55	0.1235	21
Argyll and Bute	Allt Sunadale	179950	645031	180732	644369	0.15	0.509	0.202	71	15	699.29	0.53	0.0	1.4	Pelton	80	71.8	1.2	0.6	0.26	20	0.423	0.13	0.0217	5
D&G	Garpol Spa	306505	602952	307289	603343	0.197	0.885	0.199	78	18	1100.3	0.64	1.4	1.3	Pelton	59.1	55.6	1.3	0.9	0.44	35	1.213	0.32	0.0489	13
Highland	River Fleet	266073	903530	266396	904098	0.13	0.406	0.198	68	14	585.15	0.51	0.0	0.8	Pelton	73.9	69.5	0.8	0.6	0.23	20	0.337	0.11	0.0184	7
Highland	River Moidart	176084	773630	175600	773589	0.637	1.604	0.197	84	21	1871.2	0.34	4.4	1.9	Francis	90.4	86	0.6	1	0.91	15	1.195	0.17	0.023	6
Argyll and Bute	Lochan na Cruaiche	215320	721321	214196	720444	0.194	0.691	0.194	76	17	889.18	0.52	0.3	2.5	Pelton	99.8	85.9	1.7	0.6	0.28	25	0.73	0.13	0.0342	4
Stirling	Waltersmuir Resr	280612	700193	278799	699230	0.397	1.454	0.194	83	20	1708	0.49	2.7	2.8	Pelton	149	130	2.6	0.7	0.38	20	0.62	0.15	0.0202	12
Highland	Allt Beag	174218	844557	172207	846163	0.87	3.198	0.189	87	23	3576.6	0.47	12.2	3.2	Pelton	206	177	3.0	0.8	0.61	15	0.795	0.25	0.0644	5
Perth and Kinross	Loch Glassie	287197	752635	288510	751754	0.522	1.642	0.186	84	21	1903.8	0.42	5.5	1.9	Pelton	175	160	1.9	0.7	0.4	15	0.57	0.12	0.0159	10
Argyll and Bute	Abhainn Dubhan	201090	701191	202202	701833	0.213	0.708	0.185	77	17	900.31	0.48	0.2	1.5	Pelton	82.1	72.7	1.5	0.7	0.36	25	0.883	0.13	0.0318	5
Highland	North Garvan River	196129	775815	197211	776688	0.681	1.852	0.178	85	22	2123	0.36	2.8	1.8	Francis	90.1	81.7	1.6	1.1	1.03	20	1.774	0.15	0.0155	8
Highland	Allt a' Choire Reidh	198550	785348	198710	783905	0.794	2.061	0.175	86	22	2345.8	0.34	4.8	2.0	Pelton	119	108	1.6	1	0.93	15	1.221	0.11	0.0052	4
Highland	Loch nam Breac Buidhe	238540	883224	236743	883541	0.702	2.374	0.175	86	22	2682	0.44	9.6	2.3	Pelton	218	196	2.3	0.7	0.44	15	0.591	0.16	0.0374	5
Argyll and Bute	Lochnameal	151495	753377	151535	753996	0.525	1.883	0.173	85	22	2153	0.47	7.2	0.7	Francis	71.1	67.7	0.7	1.1	0.96	20	1.392	0.45	0.0917	13
Highland	Abhainn Coire an t-Seilich	233905	894892	233824	896834	1.059	4.513	0.172	88	24	4977	0.54	18.7	2.3	Pelton	103	96.2	2.3	1.4	1.4	25	2.624	0.73	0.1633	22
Argyll and Bute	East Bay	216109	676578	216630	676482	0.186	0.555	0.171	75	16	725.28	0.45	0.5	0.7	Pelton	64.1	59	0.7	0.7	0.39	25	0.956	0.1	0.0225	5
East Ayrshire	Water of Coyle	245803	613758	245089	615228	0.192	0.828	0.171	79	18	1018.2	0.60	0.0	2.2	Pelton	82.9	70.4	2.2	0.7	0.34	30	0.651	0.21	0.0351	9
Highland	Allt na Guile	141597	832177	140815	831592	0.168	0.560	0.169	75	16	729.04	0.50	0.5	1.3	Pelton	94.1	87.4	1.1	0.6	0.24	20	0.401	0.11	0.0226	3
Highland	Strontian River	182424	764511	182071	762999	0.298	1.023	0.168	81	20	1225	0.47	1.0	2.1	Pelton	98.9	91.2	1.9	0.8	0.4	25	0.874	0.14	0.0232	5
Perth and Kinross	Falls of Barvick	285431	724053	285791	722564	0.167	0.916	0.166	81	19	1109.1	0.76	0.6	1.8	Pelton	52.1	47.1	1.8	0.9	0.44	55	3.529	0.57	0.0969	34
Midlothian	River North Esk	328894	664287	328668	664497	0.242	1.078	0.162	82	20	1280.3	0.60	0.8	0.5	Francis	21	20	0.3	1.5	1.65	40	4.524	1.36	0.208	115
Highland	Abhainn na Glasa	244867	879186	245726	879823	0.863	3.173	0.161	88	23	3529.3	0.47	11.9	1.4	Francis	69.1	64.1	1.2	1.4	1.66	20	2.568	0.81	0.2096	25
Stirling	Allt a' Mheinn	266429	734561	266879	735822	0.666	2.017	0.153	86	22	2281.4	0.39	6.5	1.5	Pelton	121	109	1.5	0.9	0.77	15	1.129	0.2	0.0326	11
Argyll and Bute	Lochan Carr Chnoic	191148	727331	190373	727735	0.211	0.615	0.152	77	18	774.74	0.42	0.3	1.0	Pelton	79.3	73	1.0	0.7	0.36	20	0.66	0.1	0.0158	5
Renfrewshire	Locher Water	239032	664382	240104	664748	0.158	0.677	0.151	79	18	840.94	0.61	0.3	1.3	Pelton	53.1	47.5	1.3	0.8	0.41	30	0.913	0.27	0.045	8
Highland	Allt a' Choire Fhionnaraich	216126	843849	216326	842447	0.695	2.181	0.151	87	23	2456	0.40	5.1	6.5	Pelton	101	93.8	1.6	1.1	0.93	20	1.611	0.22	0.0351	8
Argyll and Bute	Water of Tulla	235548	746999	234594	745774	0.161	0.894	0.149	81	19	1072.6	0.76	0.2	2.6	Pelton	50.2	45.2	1.8	0.9	0.44	55	3.855	0.57	0.1043	24
Highland	Allt a' Choire Mhair	194858	830331	194382	830094	0.229	0.685	0.147	79	18	846.98	0.42	1.2	0.8	Pelton	66.2	63.3	0.6	0.8	0.45	25	0.979	0.1	0.0083	5
Highland	Allt Each	283509	808451	285411	809184	0.221	0.997	0.145	82	20	1180.6	0.61	0.8	2.5	Pelton	95.1	81.2	2.5	0.7	0.33	30	0.741	0.21	0.0358	13
Highland	River Luineag	292562	807993	290575	811217	0.441	2.601	0.143	87	23	2901.3	0.75	0.0	4.8	Francis	82.8	65.8	4.8	1.1	0.83	55	5.248	1.14	0.2544	53
Highland	Loch Lapagial	270808	882881	271608	884064	0.167	0.748	0.140	80	19	909.65	0.62	0.0	1.9	Pelton	71.4	60.2	1.9	0.7	0.34	30	0.677	0.23	0.04	17
Argyll and Bute	Allt Mar	149969	740695	150475	740238	0.405	1.288	0.134	85	21	1484.7	0.42	5.3	0.8	Pelton	132	125	0.8	0.7	0.4	15	0.53	0.13	0.028	4
Perth and Kinross	Allt an Fhail	244159	749702	243040	750801	0.267	0.910	0.132	82	20	1076.2	0.46	1.1	2.1	Pelton	125	106	1.9	0.6	0.31	20	0.635	0.11	0.0225	5
Highland	Allt Domhain	202360	828695	202548	828144	1.032	2.285	0.131	87	23	2552.7	0.28	9.1	0.7	Pelton	140	135	0.7	1	0.96	10	0.973	0.1	0.0186	5
Inverclyde	Daff Resr	222317	671549	221259	671888	0.183	0.672	0.129	80	19	818.89	0.51	0.8	1.7	Pelton	108	100	1.5	0.6	0.22	20	0.41	0.1	0.0158	4
Argyll and Bute	Fruin Water	230633	686333	231337	685019	0.472	1.914	0.128	87	23	2152.1	0.52	1.3	2.0	Francis	54.6	50.9	1.8	1.4	1.16	35	4.497	0.58	0.0884	30
Highland	Allt Bail' a' Mhuilinn	229679	856303	230229	855261	0.542	1.725	0.122	87	22	1944.4	0.41	6.4	1.4	Pelton	140	131	1.4	0.8	0.51	15	0.705	0.16	0.0304	7
Perth and Kinross	River Knaik	282506	711633	283611	710480	0.301	1.471	0.121	86	22	1670.7	0.63	0.3	1.9	Francis	46.1	40.7	1.9	1.2	0.94	40	2.898	0.76	0.1273	35
Highland	Allt na Doire Caoile	220169	858656	220669	860006	0.19	0.811	0.120	82	20	961.9	0.58	0.0	1.8	Pelton	58.3	54.1	1.6	0.9	0.44	30	0.956	0.27	0.0585	9

Run-of-River Sites (5% Discount Rate)

County	River	Intake Easting	Intake Northing	Power house Easting	Power house Northing	Power (MW)	Total cost (M£)	NPV (M£)	LEC (£/MWh)	Discounted Payback Period	Energy production (MWh/year)	CF	Line distance (km)	Road distance (km)	Turbine type	Gross Head (m)	Net Head (m)	Penstock Length (km)	Penstock diameter (m)	Qd (m^3s^{-1})	Qd (FDC percentile)	Q10 (m^3s^{-1})	Q50 (m^3s^{-1})	Q90 (m^3s^{-1})	Catchmnet area (km^2)
Argyll and Bute	River Ruel	198845	682882	199240	683038	0.12	0.368	0.118	74	16	484.5	0.46	0.0	0.5	Pelton	50.5	48.4	0.5	0.7	0.31	25	0.74	0.1	0.0212	4
D&G	Kirkgunzeon Lane	284026	561296	283566	561641	0.194	1.037	0.117	84	21	1201.6	0.71	0.3	0.6	Francis	22.3	20.7	0.6	1.4	1.28	55	5.13	1.58	0.1915	89
Argyll and Bute	Teatle Water	214240	724637	213195	724997	0.158	0.711	0.114	82	20	849.25	0.61	0.2	1.6	Pelton	50.5	43.2	1.4	0.8	0.45	35	1.848	0.28	0.0658	10
Highland	Strontian River	181475	763570	181963	762969	0.186	0.595	0.114	80	19	725.36	0.45	0.9	0.9	Pelton	80.2	70.6	0.9	0.6	0.32	20	0.579	0.1	0.0199	3
Stirling	Allt Fathan Glinne	251894	717083	253013	717523	0.602	1.907	0.114	87	23	2134.5	0.40	3.0	1.4	Francis	67.6	60.5	1.4	1.2	1.23	25	2.939	0.3	0.0536	17
Highland	Allt na Crionaiche Bige	245187	916892	247373	916992	0.831	3.067	0.107	89	24	3374.9	0.46	9.9	4.3	Pelton	130	113	2.5	1	0.93	15	1.184	0.36	0.0789	11
Highland	Allt a' Phollain Riabhaich	213155	903168	214120	902997	0.275	0.902	0.107	84	21	1049.2	0.44	1.8	2.4	Pelton	102	94.2	1.2	0.7	0.36	20	0.606	0.11	0.0222	4
Highland	River Brora	290394	907219	291346	906867	0.106	0.417	0.106	77	17	528.08	0.57	0.0	1.2	Pelton	81.4	70.5	1.2	0.5	0.18	25	0.321	0.1	0.0172	7
South Lanarkshire	River Clyde	282815	649912	281396	649874	0.149	0.603	0.104	81	19	726.3	0.56	0.0	2.0	Pelton	90.2	80.4	1.8	0.6	0.23	25	0.379	0.12	0.0136	8
Highland	Kyle of Sutherland	256323	895044	257114	894592	0.156	0.565	0.099	81	19	681.42	0.50	0.8	1.1	Pelton	90.6	84.8	1.1	0.6	0.22	20	0.335	0.1	0.0157	6
Aberdeenshire	Haughs Bay	377190	766740	377290	766228	0.159	0.570	0.099	81	19	686.43	0.49	1.1	0.8	Pelton	62.3	59.2	0.6	0.7	0.33	20	0.532	0.14	0.0239	17
Moray	Ess of Glenlatterach (Waterfall)	319263	855111	319464	855400	0.372	1.771	0.095	88	23	1974.2	0.61	5.2	0.8	Francis	30	28.5	0.5	1.5	1.7	35	3.639	1.33	0.2702	88
Highland	Loch Airigh a' Phuill	182988	874905	182057	874984	0.343	1.143	0.093	86	22	1298.1	0.43	3.4	1.3	Pelton	92.2	85.7	1.0	0.8	0.5	20	0.851	0.15	0.0255	3
Perth and Kinross	Allt Bhaic	285837	767315	286720	765994	0.436	1.729	0.092	88	23	1927	0.50	5.1	2.0	Pelton	106	97.4	2.0	0.9	0.56	20	0.875	0.25	0.0364	18
Highland	Loch Pa iteag	250148	812396	250300	812851	0.116	0.386	0.092	78	18	483.77	0.48	0.2	0.6	Pelton	60.7	56.8	0.6	0.6	0.25	20	0.421	0.1	0.0217	4
Highland	Allt Giubhais	210269	806891	210355	805794	0.448	1.367	0.090	87	23	1536.1	0.39	4.2	2.5	Pelton	145	134	1.4	0.7	0.41	15	0.572	0.11	0.0237	3
East Dunbartonshire	Aldessan Burn	258901	680872	260584	679246	0.594	2.140	0.089	88	24	2365.1	0.45	7.7	2.6	Pelton	181	169	2.6	0.8	0.44	20	0.818	0.16	0.0312	7
Argyll and Bute	Allt Coille Chill' a' Mhoraire	144711	747069	144204	748346	0.232	0.893	0.088	85	22	1025.7	0.51	1.1	2.5	Pelton	86.7	75.1	1.6	0.7	0.38	20	0.632	0.17	0.0332	4
Aberdeenshire	Burn of Craig	347066	824790	347806	824410	0.119	0.505	0.088	81	19	608.41	0.58	0.3	1.1	Pelton	62.2	53.3	1.1	0.6	0.27	25	0.5	0.16	0.0304	11
Argyll and Bute	Loch Garasdale	175661	651670	172707	652204	0.229	1.131	0.088	86	22	1280.7	0.64	0.0	3.6	Pelton	108	90.8	3.6	0.7	0.31	35	0.701	0.22	0.0355	9
Highland	Allt Feith a' Mheallain	242836	770303	241497	770466	0.987	3.476	0.087	89	24	3798.6	0.44	12.6	1.9	Francis	90.6	82.3	1.7	1.3	1.47	25	3.386	0.51	0.0964	21
Highland	Loch a' Bha¹ic	226537	777475	225317	780518	1.608	4.556	0.087	90	25	4958.4	0.35	14.3	3.7	Pelton	269	229	3.7	0.9	0.88	15	1.171	0.12	0.0064	5
Argyll and Bute	Allt Choire Dhuibh	234999	734807	233197	735906	0.395	1.279	0.086	87	23	1438.7	0.42	0.2	2.4	Pelton	100	90.3	2.4	0.9	0.54	25	1.199	0.1	0.0053	4
Highland	Culachy Falls	237902	806133	237935	806446	0.204	1.117	0.084	86	22	1263.1	0.71	1.6	0.6	Francis	20.1	19.3	0.4	1.5	1.46	55	8.634	2.01	0.4492	73
Highland	Grudie River	232714	962815	235270	962832	0.984	4.339	0.084	90	25	4722.9	0.55	13.9	4.7	Pelton	109	102	3.0	1.4	1.22	25	2.211	0.69	0.1727	21
Renfrewshire	Caplaw Dam	243488	660126	244374	663037	0.341	1.531	0.082	88	23	1706.7	0.57	0.3	4.3	Pelton	149	125	4.3	0.7	0.34	25	0.525	0.18	0.0284	8
Perth and Kinross	Allt Baile a' Mhuilinn	257889	742489	257052	744289	1.002	2.616	0.082	89	24	2871.2	0.33	6.2	2.3	Pelton	150	133	2.3	1	0.95	15	1.361	0.12	0.0208	9
Highland	Allt na Baranachd	278400	803684	278962	802190	0.24	1.054	0.078	86	22	1191.2	0.57	2.5	1.8	Pelton	93.9	82.3	1.8	0.7	0.36	25	0.656	0.2	0.039	11
Highland	Allt a' Chumhaing	180181	840212	180415	839220	1.028	2.482	0.074	89	24	2721.3	0.30	9.5	2.2	Pelton	160	148	1.1	0.9	0.88	10	0.882	0.11	0.0109	3
Highland	Abhainn Choishleadar	134705	849693	134355	850889	0.116	0.552	0.073	83	20	648.1	0.64	0.0	1.4	Pelton	57.4	52.1	1.4	0.7	0.27	35	0.614	0.21	0.0462	6
Highland	Allt na Creadha	140625	829868	140145	831174	0.193	0.933	0.072	86	22	1056.3	0.62	1.3	1.5	Pelton	57.7	53.4	1.5	0.9	0.45	35	1.025	0.32	0.0687	8
Perth and Kinross	Black Spout	295560	759042	295051	758203	0.17	0.622	0.071	84	21	722.27	0.49	1.1	1.3	Pelton	89.8	82.8	1.1	0.6	0.25	20	0.46	0.1	0.0151	9
Perth and Kinross	Allt an Luib Bha in	253623	766157	252641	764255	0.179	0.747	0.071	85	22	855.4	0.55	0.0	2.4	Pelton	102	84.4	2.4	0.6	0.26	25	0.668	0.13	0.0281	6
Stirling	Allt Coire Cheathaich	247230	722255	247731	719652	1.392	3.883	0.071	90	25	4223.3	0.35	8.8	3.0	Pelton	150	132	3.0	1.2	1.34	15	1.831	0.19	0.0237	8
Highland	Savary River	164662	747935	164005	745718	0.409	1.699	0.063	89	24	1871.4	0.52	3.3	2.6	Pelton	102	90.8	2.6	0.9	0.56	25	1.147	0.26	0.0489	9
North Lanarkshire	Roughrigg Reservoir	277869	664192	277658	664023	0.113	0.595	0.062	85	21	686.14	0.69	1.0	0.3	Kaplan	29.9	28.9	0.3	0.9	0.47	50	1.558	0.5	0.0606	38
Highland	Alltan na Feala	207861	850639	207112	851275	0.251	0.862	0.062	87	22	972.36	0.44	0.0	1.9	Pelton	80.3	72.2	1.7	0.8	0.43	25	0.999	0.11	0.0143	5
Highland	Dunbeath Water	315523	932165	315622	930457	0.192	1.015	0.061	87	23	1135.9	0.68	0.6	2.3	Pelton	58.9	53	2.1	0.9	0.45	40	1.023	0.4	0.0842	21
Argyll and Bute	Allt Corrach	212155	686324	212741	685638	0.466	1.749	0.058	89	24	1922.3	0.47	4.0	1.0	Francis	50.4	47.1	1.0	1.3	1.24	35	4.655	0.44	0.0377	21
Highland	Allt Coir' a' Cha¹ndrain	237879	877251	237350	875725	0.343	1.241	0.057	88	23	1376.2	0.46	2.5	2.2	Pelton	102	91.9	1.8	0.8	0.46	20	0.819	0.17	0.0352	6

Run-of-River Sites (5% Discount Rate)

County	River	Intake Easting	Intake Northing	Power house Easting	Power house Northing	Power (MW)	Total cost (M£)	NPV (M£)	LEC (£/MWh)	Discounted Payback Period	Energy production (MWh/year)	CF	Line distance (km)	Road distance (km)	Turbine type	Gross Head (m)	Net Head (m)	Penstock Length (km)	Penstock diameter (m)	Qd (m^3s^{-1})	Qd (FDC percentile)	Q10 (m^3s^{-1})	Q50 (m^3s^{-1})	Q90 (m^3s^{-1})	Catchmnet area (km^2)
Argyll and Bute	Leth Uillt	172562	650606	171829	650612	0.081	0.344	0.053	82	20	409.3	0.58	0.0	0.8	Pelton	60.1	57.5	0.8	0.6	0.17	30	0.375	0.1	0.0164	5
Highland	Allt na h-Innse Buidhe	188826	777607	188539	777889	0.308	1.013	0.053	88	23	1128.4	0.42	3.9	0.5	Pelton	80.1	77.2	0.5	0.8	0.5	25	1.026	0.11	0.0033	4
Highland	Allt Coire Crubaidh	207183	853475	208712	852952	0.181	0.730	0.050	87	23	821.89	0.52	0.0	1.9	Pelton	79.7	70.6	1.9	0.7	0.32	30	1.003	0.13	0.0245	5
Highland	Allt Mar	145038	833755	146493	833133	0.171	0.757	0.050	87	23	850.81	0.57	0.0	2.4	Pelton	72.4	61.4	1.9	0.7	0.34	25	0.606	0.19	0.0423	5
Highland	Allt Loch Innis nan Seangan	193279	833464	194631	832847	0.174	0.733	0.049	87	23	824.33	0.54	0.3	3.7	Pelton	91.9	77.1	1.8	0.6	0.28	25	0.606	0.13	0.0266	5
Argyll and Bute	Allt a' Bhric	150409	743409	150689	745031	0.187	0.821	0.046	87	23	915.83	0.56	0.6	1.9	Pelton	80.9	70.9	1.9	0.7	0.32	25	0.58	0.18	0.0384	4
Highland	Allt Cille Pheadair	299133	919606	298953	918611	0.331	1.392	0.041	89	24	1526	0.53	6.2	1.1	Pelton	100	95.2	1.1	0.8	0.43	20	0.621	0.22	0.0405	10
Argyll and Bute	River Cur	213660	703713	213050	702458	0.77	2.005	0.036	90	25	2180.9	0.32	4.2	1.5	Pelton	107	103	1.5	1.2	0.94	15	1.285	0.1	0.0169	5
Highland	Allt na Fearna Mar	258863	901472	257665	901803	0.126	0.555	0.035	87	23	622.88	0.57	0.0	2.0	Pelton	72	62.1	1.5	0.6	0.25	25	0.424	0.14	0.023	8
Highland	Loch More	232123	935660	231803	936070	0.145	0.553	0.032	87	23	617.76	0.49	1.1	1.8	Pelton	76.4	72.6	0.6	0.6	0.24	20	0.416	0.11	0.0264	3
Argyll and Bute	Allt Gleann Mhic Caraidh	148248	745038	148076	745804	0.111	0.474	0.025	88	23	528.74	0.54	0.3	1.1	Pelton	64.9	58.8	1.1	0.6	0.23	25	0.447	0.12	0.0247	4
West Dunbartonshire	Burn Crooks	245726	680931	244776	682745	0.162	0.724	0.025	89	24	796.91	0.56	0.0	2.9	Pelton	113	103	2.5	0.6	0.19	25	0.35	0.11	0.0155	5
Moray	Dullan Water	331737	838312	331867	838409	0.081	0.456	0.024	88	23	508.1	0.72	0.4	0.2	Kaplan	21.3	20.8	0.2	0.9	0.47	50	1.788	0.52	0.092	37
D&G	Loch Strand	220515	557586	220111	557417	0.113	0.556	0.021	88	24	612.92	0.62	0.3	0.5	Kaplan	31	28.1	0.5	0.8	0.49	35	0.966	0.35	0.0512	15
Highland	Allt Bhuailteach	311293	927547	311473	927328	0.365	1.865	0.001	91	25	2003.3	0.63	5.9	2.4	Francis	25.3	24.4	0.3	1.6	1.97	40	4.734	1.74	0.3641	83

Run-of-River Sites (10% Discount Rate)

County	River	Intake Easting	Intake Northing	Power house Easting	Power house Northing	Power (MW)	Total cost (M£)	NPV (M£)	LEC (£/MWh)	Discounted Payback Period	Energy production (MWh/year)	CF	Line distance (km)	Road distance (km)	Turbine type	Gross Head (m)	Net Head (m)	Penstock Length (km)	Penstock diameter (m)	Qd (m^3s^{-1})	Qd (FDC percentile)	Q10 (m^3s^{-1})	Q50 (m^3s^{-1})	Q90 (m^3s^{-1})	Catchmnet area (km^2)
Highland	Falls of Kirkaig	211383	917701	209239	918874	7.643	10.796	13.2455	44	6	31622	0.47	0.6	3.35	Francis	111	99.1	2.78	2.8	9.31	20	14.42	4.33	1.0072	136.68
Highland	Abhainn Cuileig	218376	877463	219388	879105	8.537	9.2253	12.7173	42	6	28661	0.38	0.2	2.47	Francis	139	129	2.27	2.6	8	15	10.56	2.53	0.5415	62.65
Highland	Allt a' Ghlomaich	201981	825644	201095	826734	9.64	9.3353	8.79988	50	7	24234	0.29	8.49	2.17	Francis	250	246	1.77	2.5	4.73	10	4.798	0.76	0.1094	19.619
Perth and Kinross	Allt Coire a' Mhar-fhir	299560	741050	301027	741769	6.084	9.4587	8.68322	51	7	24281	0.46	8.41	1.94	Francis	80.8	74.3	1.94	3	9.93	20	16.28	4.15	0.6836	205.77
Highland	Loch Cha¹ilean Dubha	206704	867077	207606	864576	6.59	8.8667	7.23445	53	8	21700	0.38	3.88	3.1	Francis	183	178	2.9	2.5	4.48	15	5.898	1.4	0.3043	30.164
Highland	Loch an Uillt-ghiubhais	237490	855956	238719	856465	4.872	7.561	7.123	50	7	19623	0.46	1.0	1.4	Francis	58.8	52.5	1.4	3	11.4	25	23.63	4.61	0.7765	178
Highland	Allt Coire Eaghainn	217489	768908	215348	768408	7.31	9.5559	6.71749	56	8	22122	0.35	5.05	2.85	Francis	158	149	2.85	2.5	5.93	15	7.667	1.19	0.065	31.723
Highland	Loch Belivat	299562	849298	299752	849335	3.626	6.7399	6.54462	50	7	17720	0.56	7.59	0.43	Kaplan	24.3	21.1	0.23	3	20.2	25	35.42	12.4	3.0325	596.09
Highland	River Talladale	191658	867108	191864	869719	2.9	4.3626	6.49184	40	5	14114	0.56	0.2	3.41	Pelton	217	202	3.01	1.4	1.83	30	4.362	1.03	0.2272	19.76
Highland	Loch a' Bha na	222046	831240	222838	831410	4.42	6.547	5.939	51	7	16724	0.43	0.2	1.0	Francis	48.6	43.5	1.0	3	12.5	25	25.6	4.36	0.5805	130
Highland	Loch Bad na Goibhre	210119	923410	209599	923080	3.441	5.2922	5.92935	46	6	14841	0.49	1.37	0.68	Francis	44.8	42.5	0.68	3	10	25	18.7	5.29	1.1897	164.45
Highland	River Glass	258334	866446	259768	866816	3.925	5.831	5.653	50	7	15320	0.45	0.2	1.7	Francis	79.6	73.7	1.7	2.5	6.48	20	10.36	2.68	0.5455	116
Perth and Kinross	Allt a' Chrombaidh	277059	768228	280597	765513	4.931	13.494	5.22936	67	12	26250	0.61	0.77	5.19	Francis	81.4	68.3	4.99	3	8.77	35	26.48	6.23	1.3513	258.93
Perth and Kinross	Falls of Bruar The	282041	768041	282335	765977	5.243	7.8124	5.14961	57	9	17685	0.39	2.73	2.64	Francis	161	157	2.64	2.5	4.03	15	5.526	1.4	0.3405	66.989
Highland	Loch Kirkaig	208306	919330	207972	919340	2.705	3.9616	4.94014	44	6	11697	0.49	0.6	1.48	Francis	42.5	41.3	0.38	2.8	8.11	25	14.74	4.44	1.0225	140.79
Highland	River E	251646	811979	249525	814331	3.807	8.8006	4.69807	61	10	18629	0.56	0	4.3	Francis	96.2	86.2	4.1	2.5	5.36	30	11.95	3.47	0.9051	114.95
Highland	Lochan na Craoibhe-beithe	254419	824658	252056	823948	1.776	3.9973	4.28734	47	7	10985	0.71	3.43	3.56	Pelton	171	154	3.56	1.3	1.46	45	4.693	1.46	0.3314	73.15
Perth and Kinross	Burn of Auchrannie	329511	751555	329610	750731	2.993	5.7086	4.11231	56	8	13332	0.51	6.9	0.89	Francis	47.1	44.1	0.89	2.8	8.38	25	16.19	4.41	0.7891	289.9
Highland	Abhainn Droma	220940	877640	220110	878223	3.41	4.3262	3.87209	51	7	10989	0.37	0	1.14	Francis	102	101	1.14	2.5	4.11	15	5.461	1.27	0.275	37.854
Highland	Allt an Ruighe	191828	824511	190612	823105	3.44	4.478	3.74625	53	8	11068	0.37	6.13	2.11	Pelton	263	239	2.11	1.2	1.83	15	2.471	0.39	0.0744	11.477
Highland	Lochain a' Mhill Dheirg	231417	932994	229841	933040	3.267	4.6583	3.70864	54	8	11293	0.39	4.81	9.36	Pelton	220	211	1.99	1.5	1.97	15	2.628	0.57	0.1242	13.775
Highland	Loch Belivat	299958	849634	300007	849754	2.402	5.4394	3.67475	57	9	12418	0.59	7.82	0.14	Kaplan	17.5	16	0.14	3	17.7	30	35.4	12.4	3.0344	596.58
Highland	Loch Kirkaldy	293521	842892	213319	800410	2.361	5.2345	3.5985	57	9	12023	0.58	8.18	0.29	Kaplan	17.3	16.4	0.09	3	16.9	30	33.99	11.8	2.8819	550.55
Highland	Allt Briste	226123	935030	224983	934037	2.417	4.0214	3.59286	51	7	10207	0.48	6.79	6.34	Pelton	184	170	1.84	1.3	1.81	20	2.954	0.76	0.1753	21.633
Highland	Loch na h-Uidhe	194274	887470	194733	889962	3.797	8.2519	3.5844	65	11	16506	0.5	7.06	3.17	Francis	97.9	91	3.17	2.5	5.06	25	9.328	2.5	0.5134	78.873
Highland	River Lair	198937	850207	200131	848245	2.917	3.4189	3.41815	49	7	9104.2	0.36	0	2.99	Pelton	329	292	2.79	1	1.26	15	1.665	0.22	0.0351	6.7027
Highland	Allt a' Mhuilinn	216086	773054	213876	775654	3.511	3.9796	3.39149	52	8	9909	0.32	1.33	3.93	Pelton	479	417	3.93	0.9	1.06	10	1.062	0.14	0.0016	3.5073
Highland	Allt Coire an Eich	254778	804711	253608	806894	2.513	4.8187	3.30339	57	9	11057	0.5	7.53	4.21	Pelton	216	197	3.11	1.3	1.62	20	2.57	0.79	0.2227	24.525
Highland	Allt a' Chonais	206765	848429	205509	848892	3.074	3.5316	3.24756	51	7	9072.3	0.34	0.77	1.76	Francis	171	164	1.56	1.6	2.27	15	2.942	0.42	0.0441	12.515
Highland	Loch Kirkaldy	293242	843151	293304	843381	2.113	5.2944	3.21103	59	9	11658	0.63	7.7	0.49	Kaplan	19	16.8	0.29	3	14.8	35	33.99	11.8	2.885	551.56
Highland	Allt Lochain Buidhe	212103	881511	211921	884763	2.334	5.4696	3.20068	60	9	11907	0.58	6.28	4.54	Pelton	221	199	4.54	1.3	1.49	30	3.225	0.92	0.2284	24.815
Argyll and Bute	Eagle's Fall	222706	714223	221588	714815	3.322	3.1174	2.94298	50	7	8097.7	0.28	3.38	1.45	Pelton	371	354	1.45	1	1.19	10	1.209	0.14	0.0357	5.0617
Highland	Allt Ban an Laruighe	197883	826084	198421	827001	2.63	3.0017	2.91829	49	7	7896.2	0.34	5.94	1.36	Pelton	327	304	1.36	0.9	1.09	10	1.125	0.26	0.055	6.0832
Highland	Abhainn Chia-aig	218137	790483	217597	788890	2.635	4.5612	2.8304	59	9	10119	0.44	11	1.92	Pelton	190	174	1.92	1.3	1.94	25	4.318	0.52	0.0743	19.437
Highland	Rogie Falls	244654	858496	244804	857621	1.996	5.501	2.805	62	10	11489	0.66	2.9	1.4	Francis	31.3	28	1.2	3	9.08	45	32.26	8.85	1.9292	317
Highland	Allt Cam Ba n	256206	806559	253707	807019	2.629	4.745	2.78849	60	9	10344	0.45	7.33	4.73	Pelton	290	262	3.43	1.1	1.27	15	1.667	0.52	0.1446	15.487
Highland	Allt na Fa¨ithe Buidhe	194297	832050	194061	831383	2.406	4.6566	2.77328	59	9	10194	0.48	0	1.05	Francis	34.6	32.3	0.77	3	9.36	30	23.82	4.49	0.8177	131.1
Highland	Allt Coire na Creiche	186486	761764	185282	760779	2.288	2.7264	2.72255	49	7	7256.3	0.36	0.2	1.91	Pelton	255	230	1.91	1	1.26	15	1.647	0.23	0.0338	5.4508
Highland	Lochan nan Leacann Dearga	182488	867215	181371	869295	1.526	3.6703	2.66273	56	8	8593.7	0.64	3.51	6.07	Pelton	155	142	3.1	1.3	1.37	40	4.381	1.12	0.2542	21.048

Run-of-River Sites (10% Discount Rate)

County	River	Intake Easting	Intake Northing	Power house Easting	Power house Northing	Power (MW)	Total cost (M£)	NPV (M£)	LEC (£/MWh)	Discounted Payback Period	Energy production (MWh/year)	CF	Line distance (km)	Road distance (km)	Turbine type	Gross Head (m)	Net Head (m)	Penstock Length (km)	Penstock diameter (m)	Qd (m^3s^{-1})	Qd (FDC percentile)	Q10 (m^3s^{-1})	Q50 (m^3s^{-1})	Q90 (m^3s^{-1})	Catchmnet area (km^2)
South Ayrshire	Water of Fail	239516	623458	239338	623533	1.561	3.7843	2.61738	57	9	8710.6	0.64	1.4	0.41	Kaplan	15.4	14.2	0.21	3	13	40	33.71	10.6	1.5662	567.52
Highland	Black Water or Uisge Dubh	200036	837629	200028	836657	3.56	5.2338	2.58058	63	10	10829	0.35	4.2	3.45	Francis	77.1	74	1.07	2.5	5.85	15	7.826	1.48	0.2787	36.731
Highland	Allt Airdeasaidh	204763	888562	205304	889740	3.769	5.115	2.41858	64	11	10462	0.32	15	1.54	Pelton	288	272	1.54	1.2	1.77	10	1.803	0.33	0.06	12.348
Highland	Abhainn na Fa¹irneis	197971	870385	195947	870680	2.773	4.4435	2.34839	62	10	9378.2	0.39	7.73	3.35	Pelton	263	233	2.58	1.1	1.51	15	2.001	0.36	0.059	8.7131
Stirling	Allt Dha¹in Croisg	253754	738017	252852	736302	2.714	3.3625	2.3404	56	9	7757	0.33	0	2.5	Pelton	255	228	2.3	1.1	1.51	15	2.132	0.19	0.0322	8.9424
Highland	Allt Coire an Eoin	221995	775326	223223	777454	2.848	5.665	2.32553	66	11	11173	0.45	11.2	3.57	Pelton	219	203	3.17	1.4	1.78	25	3.546	0.54	0.0406	13.414
Highland	River E	254637	813629	251994	816472	1.739	3.6435	2.32026	58	9	8152.3	0.54	0.2	4.98	Pelton	301	245	4.98	0.9	0.89	20	1.396	0.45	0.1191	16.226
Scottish Borders	Hirsel Lake	388855	642554	388693	642660	1.566	3.3752	2.2926	57	9	7719.9	0.56	1.2	0.21	Francis	21.9	21.2	0.21	3	9.68	35	21.96	6.8	0.911	664.16
Highland	Tollie Bay	186970	878852	186882	878930	1.449	3.899	2.27992	60	9	8486.1	0.67	0.77	0.32	Kaplan	11.3	10.1	0.12	3	17	45	66.8	16.3	3.3932	430.03
Argyll and Bute	Lochan Sran Mar	216271	719231	214952	716563	2.417	4.0424	2.12168	62	10	8514.4	0.4	0.2	3.35	Pelton	220	203	3.35	1.3	1.51	20	2.618	0.35	0.069	13.31
Argyll and Bute	Garbh-allt Mar	221476	713017	220464	713799	2.293	2.2522	2.08216	51	7	5798.7	0.29	1.88	1.53	Pelton	388	364	1.53	0.8	0.79	10	0.804	0.1	0.0265	4.1708
East Ayrshire	Burnock Water	250514	621568	250323	621819	1.39	2.7485	2.07845	55	8	6534.3	0.54	0.28	0.53	Francis	29.9	28.8	0.33	2.5	6.14	30	12	3.81	0.5721	204.04
Argyll and Bute	Allt nam Muc	204324	707148	205440	704907	1.458	2.9771	2.04436	57	9	6835.2	0.54	0.2	3.12	Pelton	163	146	3.12	1.2	1.26	30	4.041	0.58	0.1406	20.745
Highland	River Grudie	195852	865320	196387	867081	1.175	2.5983	1.98257	55	8	6198.1	0.6	0.57	2.71	Pelton	108	103	2.11	1.5	1.45	40	5.347	1.02	0.1634	22.228
Argyll and Bute	Eas an Amair	200794	713126	199616	713445	1.299	1.8981	1.98119	48	7	5152.3	0.45	0.2	1.59	Pelton	174	166	1.59	1.1	0.99	20	1.843	0.38	0.0875	8.8809
Stirling	Falls of Leny	259176	708718	259848	708813	2.165	4.8415	1.94602	66	11	9500.1	0.5	0.4	0.82	Francis	29.7	26.7	0.82	3	10.3	35	34.4	5.15	0.626	195.62
Highland	Loch Cuileig	226019	815045	226679	812997	1.346	2.3531	1.85882	54	8	5687.4	0.48	0.6	2.49	Pelton	201	183	2.49	1	0.92	20	1.52	0.39	0.0918	11.728
Highland	Allt Grannda	202385	817090	200799	817294	3.584	5.742	1.82024	70	13	10696	0.34	16.1	3.72	Francis	214	205	1.91	1.5	2.13	15	2.744	0.4	0.0118	8.9973
Stirling	Allt Criche	232824	718151	232121	718584	3.289	3.9522	1.80321	64	11	8006.7	0.28	12.6	1.16	Pelton	275	263	0.96	1.1	1.59	10	1.604	0.14	0.0217	6.7753
Argyll and Bute	Donich Water	221366	701853	220229	701927	2.003	2.5965	1.79652	57	9	5977.3	0.34	0.48	1.38	Pelton	150	140	1.38	1.3	1.82	15	2.393	0.25	0.0146	6.5097
Perth and Kinross	Allt a' Mha gain	292649	765152	291180	762873	1.859	3.6544	1.73748	64	11	7485.6	0.46	2.08	3.1	Pelton	168	151	3.1	1.3	1.56	20	2.786	0.55	0.0962	36.372
Highland	An Garbh-allt	178757	851756	178609	854705	1.858	4.3754	1.72693	67	12	8548.4	0.53	4.19	5.01	Pelton	193	167	3.91	1.2	1.41	25	2.762	0.66	0.136	16.631
Argyll and Bute	Allt Beochlich	202241	715212	200573	715376	1.423	2.1539	1.70453	54	8	5209.6	0.42	0.2	2.11	Pelton	212	198	2.11	1	0.9	20	1.66	0.26	0.0606	9.1735
Argyll and Bute	River Shira	214053	713064	212946	713387	1.339	1.7391	1.70352	49	7	4589.8	0.39	0.2	1.35	Pelton	190	172	1.35	0.9	0.98	15	1.383	0.28	0.0657	6.0398
Highland	Lochan na Beinne	212945	895362	212443	894494	1.625	3.7654	1.69006	65	11	7595.5	0.53	0.77	1.24	Francis	48.5	46.5	1.24	2.5	4.32	30	9.767	2.64	0.6029	82.542
Highland	Allt Garaidh Ghualaich	215762	798809	217039	800471	1.326	2.754	1.660	59	9	6052.4	0.52	0.8	2.5	Pelton	130	111	2.5	1.2	1.51	25	3.22	0.69	0.1501	17
Highland	Allt a' Choire Dhuibh	202056	836104	200276	836364	1.343	3.2989	1.61834	63	10	6815.8	0.58	4.4	5.18	Pelton	121	108	2.31	1.3	1.57	35	4.963	0.93	0.1735	34.746
Highland	River Farrar	232384	841193	231996	839879	1.151	1.4028	1.56648	46	6	3927.7	0.39	0.2	1.57	Pelton	319	301	1.57	0.7	0.47	15	0.685	0.14	0.0311	3.8643
Argyll and Bute	Allt Cnoc an Tighe	225146	733949	224706	732899	1.814	5.2152	1.55831	71	13	9602.9	0.6	1.53	1.44	Francis	30.5	27.5	1.24	3	8.41	45	48.28	7.23	1.2129	233.95
Highland	Allt Coire na Ba	216697	762739	216574	761987	1.688	2.1806	1.53852	56	8	5054.7	0.34	0.48	0.89	Pelton	119	112	0.89	1.3	1.93	15	2.495	0.26	0.0083	10.159
Highland	Loch Mar	299061	824803	300185	824330	1.596	4.5696	1.50939	69	13	8583	0.61	1.41	1.81	Francis	40.2	36	1.61	2.5	5.56	35	12.56	4.31	0.8808	270.97
Highland	Allt Coire Giubhsachan	218320	769726	218662	768734	2.682	3.4969	1.50816	65	11	6982	0.3	6.97	9.67	Pelton	270	252	1.19	1	1.35	10	1.352	0.14	0.0042	4.1903
Highland	River Coiltie	247163	827048	250116	828318	1.44	3.4923	1.49921	65	11	6964.6	0.55	0.57	3.91	Pelton	157	132	3.91	1.2	1.39	25	2.835	0.7	0.1349	33.892
Aberdeenshire	Loch Kinord	345940	798215	346127	798225	1.074	3.6344	1.49447	66	11	7171	0.76	1.2	0.2	Kaplan	10.2	8.72	0.2	3	14.7	55	69.81	19.4	4.3851	1029.7
Highland	Alness River or River Averon	263360	872868	263408	872637	1.152	2.662	1.487	61	10	5711.9	0.57	0.6	0.5	Francis	24.2	23.4	0.3	2.6	6.42	35	15.86	4.69	1.0151	195
Highland	Allt Coire na Ba	219120	763688	218716	762397	1.726	2.1935	1.44591	57	9	4965.4	0.33	0.57	1.52	Pelton	217	208	1.52	1.1	1.04	15	1.365	0.11	0.0005	4.4229
Highland	Allt a' Choire Dhuibh Mhair	194706	859006	196077	857253	2.488	3.4438	1.40587	66	11	6782.8	0.31	8.77	2.94	Pelton	463	430	2.54	0.8	0.72	10	0.73	0.11	0.0082	2.1715
Highland	Allt na Claise Brice	171615	747109	170766	747248	0.951	1.9434	1.40234	56	8	4541.4	0.55	1.33	0.98	Francis	72.2	67.7	0.98	1.4	1.73	30	3.785	1.04	0.2104	28.617
Highland	Allt a' Choire Ghlais	226161	796553	227914	795793	2.335	3.5893	1.3964	67	12	6988.8	0.34	5.2	2.64	Pelton	269	238	2.44	1	1.24	15	1.672	0.17	0.0231	8.7225
Highland	Loch Pa iteag	249378	814479	248918	815370	1.693	5.15	1.39517	72	14	9314.5	0.63	0.2	2.38	Francis	52.4	48.7	2.38	2.5	4.3	40	13	3.76	0.9745	128.83

Run-of-River Sites (10% Discount Rate)

County	River	Intake Easting	Intake Northing	Power house Easting	Power house Northing	Power (MW)	Total cost (M£)	NPV (M£)	LEC (£/MWh)	Discounted Payback Period	Energy production (MWh/year)	CF	Line distance (km)	Road distance (km)	Turbine type	Gross Head (m)	Net Head (m)	Penstock Length (km)	Penstock diameter (m)	Qd (m^3s^{-1})	Qd (FDC percentile)	Q10 (m^3s^{-1})	Q50 (m^3s^{-1})	Q90 (m^3s^{-1})	Catchmnet area (km^2)
South Lanarkshire	Stonebyres Falls	287108	644808	286869	644432	1.126	2.3495	1.35754	60	9	5094.5	0.52	0.77	0.51	Francis	45.5	45.1	0.51	2.5	3.1	25	5.135	1.75	0.2528	119.39
Highland	Loch a' Bhaid-bheithe	250226	892607	251482	892564	2.058	6.414	1.315	75	15	11106	0.62	5.9	1.5	Francis	32.5	28.1	1.5	3	9.3	40	29.61	7.65	1.6294	247
Argyll and Bute	River Goil	217529	700097	218517	700197	1.513	1.9648	1.30423	57	9	4458.4	0.34	0	1.23	Pelton	149	137	1.23	1.1	1.41	15	1.871	0.17	0.0153	8.4613
Highland	Allt Poll Doire	171147	752370	170194	750667	0.9	2.2318	1.29825	60	9	4849.5	0.61	0	2.39	Francis	90.8	81.9	2.19	1.3	1.35	40	4.957	1.04	0.1963	27.571
Highland	Alltan Odhar	195118	847491	195401	845706	1.296	2.4715	1.29469	62	10	5202.8	0.46	0.77	2.6	Pelton	129	115	2.03	1.2	1.43	25	2.931	0.44	0.0591	12.223
Stirling	Dubh Eas	230120	720575	231881	719894	2.099	4.4753	1.29294	71	13	8188.6	0.45	11.2	2.35	Pelton	177	168	2.35	1.4	1.59	25	3.706	0.46	0.1013	21.304
Highland	Allt Gleann a' Mhadaidh	221357	885810	218864	885430	1.008	2.1614	1.28199	60	9	4725.5	0.54	0	3.05	Pelton	180	165	3.05	1	0.76	25	1.479	0.4	0.0998	7.0098
Argyll and Bute	Abhain a' Bhealaich	197205	705639	195785	707516	1.101	2.2213	1.26976	60	10	4800.5	0.5	0.28	2.82	Pelton	170	151	2.82	1	0.92	25	2.254	0.37	0.0931	12.523
Highland	Loch a' Mheallain Odhair	208440	866621	208537	864456	1.362	3.1907	1.26446	67	12	6239.8	0.52	4.44	2.63	Pelton	143	127	2.63	1.2	1.36	25	2.734	0.65	0.1394	16.527
Highland	Allt Guibhais	206321	863031	204961	862316	1.763	4.9041	1.25784	73	14	8786.9	0.57	0.4	1.7	Francis	40.1	35.5	1.7	2.6	6.22	35	17.7	4.26	0.9459	111.6
Highland	Allt Coire Mhuillidh	227595	839651	293449	842935	1.484	1.9876	1.22586	59	9	4400.6	0.34	0	1.43	Pelton	161	150	1.43	1.1	1.25	15	1.692	0.18	0.0219	9.0509
Argyll and Bute	Allt Lairig lanachain	212258	731007	212916	729799	1.459	2.0234	1.22325	59	9	4450.8	0.35	0.2	1.72	Pelton	166	155	1.52	1.1	1.19	15	1.537	0.18	0.0024	2.7622
Perth and Kinross	Allt Conait	253526	745199	254084	745267	1.852	4.5313	1.21265	72	14	8178.1	0.5	4.84	1.05	Francis	29.8	27.9	0.65	2.9	8.45	35	30.58	4.43	0.7312	161.25
Highland	Allt a' Charnaich	234789	802958	234092	803249	0.904	1.5395	1.20627	54	8	3709.3	0.47	0.48	0.9	Francis	93.6	88.9	0.9	1.2	1.25	25	2.849	0.54	0.0958	23.672
Highland	Allt a' Chraois	244649	939543	245179	942511	1.753	4.8982	1.20567	73	14	8717.1	0.57	12.3	3.45	Pelton	170	154	3.45	1.3	1.44	30	3.257	0.82	0.1713	19.313
Angus	Falls of Damff	338510	778898	338825	780271	2.512	4.7641	1.20091	73	14	8511.5	0.39	17.3	2.3	Pelton	250	234	1.7	1.1	1.36	15	2.036	0.37	0.0665	26.525
Highland	Achness Waterfall	246723	903397	246743	902747	1.954	5.754	1.168	75	15	9949.3	0.58	10.9	1.1	Francis	28.9	26.5	0.8	3	9.44	35	22.81	7.14	1.7076	179
Argyll and Bute	Allt Arnan	230697	716730	231440	716674	1.992	2.9386	1.15434	67	12	5734.7	0.33	14.1	0.85	Pelton	206	199	0.85	1.1	1.27	15	1.712	0.16	0.03	6.2132
Highland	River Farrar	236086	839160	237068	839402	1.667	5.153	1.153	74	15	9034.6	0.62	0.6	1.2	Francis	26.4	22.7	1.2	3	9.55	45	43.91	8.61	1.5045	276
Highland	Allt Easgadill	179099	759005	178787	759747	0.694	0.956	1.14948	45	6	2772.8	0.46	0	0.91	Pelton	178	172	0.91	0.8	0.5	15	0.628	0.21	0.0486	4.5444
Perth and Kinross	Burn of Auchrannie	328462	752682	328545	752597	1.239	2.9574	1.14858	67	12	5756.1	0.53	6.44	0.64	Francis	31.4	31.1	0.16	2.5	5.06	30	12.22	3.04	0.5706	173.93
Highland	Water of Glencalvie	243690	888782	246066	888844	3.376	8.605	1.136	79	17	14162	0.48	12.8	3.2	Francis	83.1	75.7	3.0	2.5	5.43	25	10.78	2.53	0.5772	72
South Lanarkshire	Wellbrae Resrs	273509	653181	273515	653378	1.146	2.9134	1.10304	67	12	5637.1	0.56	2.17	0.48	Francis	20.6	20	0.2	2.8	7.59	35	16.91	5.45	0.8298	269.03
Highland	River Farrar	235232	841584	237181	839806	1.115	1.961	1.09988	61	10	4213.2	0.43	0.2	3.26	Pelton	318	278	3.26	0.7	0.5	20	0.977	0.15	0.0294	7.7794
Highland	Allt na Fea rna	236788	808803	236900	808979	0.992	3.452	1.098	70	13	6434.8	0.74	0.3	0.4	Kaplan	10.1	8.5	0.2	3	14	55	84.08	18.8	3.3723	486
Perth and Kinross	Loch Farleyer	280970	750462	281599	749420	0.955	1.4018	1.09823	54	8	3377.5	0.4	0.6	1.43	Pelton	209	195	1.43	0.8	0.61	15	0.885	0.18	0.0225	14.484
Aberdeenshire	Burn of Glendui	342443	796627	342638	796647	1.037	3.792	1.08371	71	13	6924.5	0.76	2.83	0.49	Kaplan	10.1	8.61	0.21	3	14.4	55	68.7	19	4.3068	1007.8
Argyll and Bute	Eas a' Ghaill	222674	727045	220443	727267	3.632	6.8995	1.07985	78	17	11554	0.36	5.08	2.71	Francis	105	101	2.51	2.5	4.36	20	7.533	0.84	0.1038	32.641
Highland	Loch Bra igh Horrisdale	179430	871054	178899	871424	1.706	3.5838	1.07899	71	13	6608.6	0.44	4.77	2.24	Francis	56	55.1	0.76	2.5	3.81	20	5.889	1.7	0.3888	36.533
Highland	Allt Raon a' Chroisg	218546	888760	217317	888410	0.794	1.1923	1.07298	51	7	3035.4	0.44	0.4	1.6	Pelton	262	231	1.6	0.6	0.43	15	0.573	0.15	0.0341	4.0731
Argyll and Bute	Eas na Gea rr	199227	737178	198826	735490	1.987	3.0435	1.05313	69	12	5772.6	0.33	0.28	2.27	Pelton	168	154	2.27	1.3	1.64	15	2.131	0.18	0.0188	12.625
Highland	Allt a' Chnaip Ghiubhais	237153	919176	238400	917405	2.402	6.289	1.053	77	16	10611	0.5	3.0	2.5	Francis	68.8	64.3	2.5	2.5	4.57	25	8.597	2.48	0.6107	49
Highland	Garbh Allt	237597	931485	238346	931965	1.077	1.639	1.043	58	9	3666.9	0.39	1.6	4.0	Pelton	170	165	1.0	1	0.82	15	1.092	0.23	0.0516	7
Highland	Allt Eiteachan	260784	886524	262962	887725	0.87	2.123	1.036	63	10	4379	0.57	0.0	2.9	Pelton	141	122	2.9	1	0.9	25	1.559	0.52	0.1079	23
Highland	Allt Choire a' Chait	210679	812487	210709	811286	2.084	2.8523	1.03534	68	12	5466.6	0.3	8.38	1.35	Pelton	341	318	1.35	0.8	0.82	10	0.835	0.11	0.0175	2.5405
Highland	Allt Uchd Rodha	225676	839583	225729	838563	0.892	1.2935	1.03248	54	8	3138.9	0.4	0	1.3	Pelton	177	169	1.3	0.9	0.66	20	1.198	0.17	0.0325	6.9471
Highland	Allt Coire an t-Sneachda	219519	825898	220919	824100	1.861	4.063	1.024	73	14	7259.4	0.45	7.3	3.1	Pelton	170	155	2.8	1.3	1.53	25	3.593	0.45	0.0807	18
Perth and Kinross	Black Water	314330	755313	314606	751817	3.157	9.1527	1.01556	80	18	14838	0.54	1.05	4.6	Francis	80.9	69.5	4.4	2.5	5.54	30	14.72	2.91	0.4902	179.73
Highland	Allt Gleann Chaorachain	210382	885379	211142	885882	1.804	3.0718	1.00645	69	13	5760	0.36	7.58	1.22	Pelton	151	140	1.22	1.2	1.63	15	2.149	0.34	0.0519	9.7259
Highland	Abhainn Droma	219974	878450	219709	878665	0.657	1.3838	1.0061	56	8	3242.6	0.56	0	0.36	Francis	40.7	39.5	0.36	1.6	2.09	35	6.079	1.45	0.3126	43.632

Run-of-River Sites (10% Discount Rate)

County	River	Intake Easting	Intake Northing	Power house Easting	Power house Northing	Power (MW)	Total cost (M£)	NPV (M£)	LEC (£/MWh)	Discounted Payback Period	Energy production (MWh/year)	CF	Line distance (km)	Road distance (km)	Turbine type	Gross Head (m)	Net Head (m)	Penstock Length (km)	Penstock diameter (m)	Qd (m^3s^{-1})	Qd (FDC percentile)	Q10 (m^3s^{-1})	Q50 (m^3s^{-1})	Q90 (m^3s^{-1})	Catchmnet area (km^2)
Highland	Allt na Fea rna	232618	811989	232368	813431	0.796	1.4542	0.97301	57	9	3308.8	0.47	0.68	1.75	Pelton	176	167	1.75	0.9	0.59	20	0.946	0.25	0.0566	8.8
Highland	Allt Coire nam Bra than	231590	840606	231975	839921	0.963	1.1669	0.96935	53	8	2876.1	0.34	0.2	0.88	Pelton	207	199	0.88	0.8	0.6	15	0.846	0.1	0.0207	3.4561
Highland	Allt a' Choire Bhuidhe	257923	818038	256324	819702	0.9	1.9933	0.96786	63	10	4106.7	0.52	2.26	2.99	Pelton	271	239	2.99	0.7	0.47	20	0.734	0.23	0.0592	8.4826
Perth and Kinross	Falls of Keltney	276759	750366	277419	748962	0.981	2.0619	0.95582	64	11	4194.8	0.49	0.48	1.82	Pelton	100	93.1	1.82	1.3	1.34	25	3.333	0.51	0.0659	32.994
Perth and Kinross	Allt an Fhionn	266648	725930	267022	724709	1.265	1.915	0.95274	63	10	3972.2	0.36	1.97	1.44	Pelton	189	171	1.44	0.9	0.93	15	1.348	0.19	0.0298	11.92
Argyll and Bute	Leth Allt	205796	690273	204078	690388	1.309	2.2347	0.9412	66	11	4435.4	0.39	0.4	2.16	Pelton	165	152	2.16	1.1	1.09	20	1.946	0.21	0.0449	8.5836
Highland	Allt an Reinidh	235736	936803	234544	936121	0.999	1.4734	0.93597	58	9	3294.1	0.38	1.53	1.71	Pelton	282	266	1.51	0.7	0.47	15	0.622	0.11	0.019	3.474
Highland	River Douchary	225466	891467	225509	893086	1.328	3.7666	0.93337	73	14	6710.4	0.58	9.44	4.22	Pelton	123	112	2.25	1.3	1.51	30	3.693	0.92	0.2114	28.465
Highland	River Taodail	195862	841724	194433	842135	0.983	2.0555	0.92133	65	11	4144.9	0.48	0.2	2.05	Pelton	100	92.7	1.85	1.3	1.34	25	2.966	0.5	0.0892	14.071
Highland	Allt a' Bhuiridh	177255	780227	177899	781746	1.402	2.1531	0.9081	66	11	4274.9	0.35	0.88	3.07	Pelton	211	198	1.9	1	0.89	15	1.159	0.14	0.0121	5.1329
Highland	Abhainn Loch na h-Oidhche	188248	867242	187248	869387	1.595	3.6051	0.90337	73	14	6434.5	0.46	2.83	6.46	Pelton	193	166	3.48	1.1	1.21	20	1.968	0.43	0.0883	9.4962
Highland	Allt Toll a' Mhuic	223194	840373	222486	839140	1.203	1.6666	0.90109	61	10	3541.3	0.34	0	1.63	Pelton	210	197	1.63	0.9	0.77	15	1.036	0.12	0.0187	4.4579
Stirling	Allt Fionn Ghlinne	232211	722394	233220	720735	2.643	4.6509	0.90101	76	15	7991.1	0.35	10.5	2.26	Pelton	209	193	2.26	1.3	1.74	15	2.347	0.27	0.0473	10.282
Argyll and Bute	Allt Dhoirrean	215556	732418	215648	730935	1.225	1.7758	0.8973	62	10	3699.5	0.34	0.2	1.72	Pelton	199	182	1.72	0.9	0.85	15	1.095	0.11	0.0012	2.0335
Stirling	Allt nan Sliseag	245068	729984	245323	728407	2.193	3.6285	0.86304	74	14	6422.2	0.33	9.06	2.1	Pelton	257	235	1.9	1	1.18	15	1.663	0.17	0.0406	6.421
Argyll and Bute	Kames River	199320	710182	198176	710466	0.723	1.1734	0.86257	55	8	2760.7	0.44	0.4	1.52	Pelton	170	159	1.32	0.8	0.56	20	1.051	0.19	0.0426	6.7896
Highland	Loch Garbhaig	189793	870245	189508	871234	0.735	1.1204	0.85113	55	8	2668.2	0.41	0	1.28	Pelton	171	160	1.28	0.8	0.57	15	0.771	0.19	0.0429	5.4816
Scottish Borders	Leader Water	356073	639896	356220	639774	0.88	2.1386	0.84944	67	12	4184.6	0.54	1.4	0.21	Francis	26	25.6	0.21	2.5	4.44	30	8.455	2.86	0.4274	236.42
Highland	Mathair a' Gharbh Uilt	227743	950379	226892	949850	0.92	2.1613	0.84466	67	12	4212.7	0.52	2.1	3.92	Francis	80.6	73.7	1.31	1.3	1.54	30	3.619	0.82	0.1477	24.365
Stirling	River Dochart	249293	730367	250989	729522	2.135	3.408	0.83768	73	14	6063.7	0.32	4.6	2.44	Pelton	257	228	2.44	1	1.18	15	1.649	0.12	0.0249	6.8349
Argyll and Bute	Allt Arnan	230548	718894	231668	718417	2.23	3.6298	0.83489	74	15	6391.1	0.33	12.7	1.35	Pelton	217	209	1.35	1.2	1.35	15	1.81	0.16	0.0259	6.6744
Highland	River Broom	220150	881987	219430	881380	0.656	0.8972	0.81923	51	7	2298	0.4	0	1.03	Pelton	230	223	1.03	0.7	0.36	15	0.491	0.11	0.0229	3.2605
Highland	Allt Duasdale Mar	219294	901640	217595	902742	0.842	2.1492	0.81552	67	12	4160.5	0.56	0	2.43	Francis	97.4	85.6	2.43	1.2	1.21	30	2.58	0.77	0.1811	22.823
Highland	Allt Gartain	217581	751067	216967	750987	2.128	5.0471	0.78945	78	17	8451.2	0.45	7.84	0.96	Francis	35.8	33.5	0.76	2.8	7.98	30	21.73	3.06	0.468	96.611
Highland	Allt Garbh-choire	218626	836768	219481	838006	0.88	1.394	0.775	61	10	2986.7	0.39	0.0	1.8	Pelton	215	201	1.8	0.8	0.54	20	0.974	0.11	0.0154	3
Highland	Allt a Gheallaidh	317633	836410	317560	836494	0.936	3.0586	0.76558	73	14	5458.2	0.67	2.38	0.12	Kaplan	10.4	9.88	0.12	3	11.3	40	30.55	10.2	2.3567	544.37
Stirling	Falls of Dochart	256980	732343	257387	732740	1.205	3.6523	0.7631	75	15	6340.5	0.6	0.4	0.6	Francis	20.3	18.8	0.6	3	8.58	45	44.16	7.6	1.3215	235.38
Highland	Allt Baile nan Carn	227539	814681	227299	813166	0.65	1.2479	0.76225	59	9	2754.1	0.48	0.6	1.72	Pelton	171	159	1.72	0.8	0.51	20	0.824	0.22	0.0515	7.2717
Dumfries and Galloway	Cargen Pow	296845	576109	297053	575911	1.058	4.1899	0.75697	76	16	7135	0.77	0.2	0.29	Kaplan	10.3	7.13	0.29	3	17.9	55	102.1	22.3	3.2697	1114.3
Highland	Abhainn Ghardail	183511	754738	183556	753311	1.124	1.9494	0.75316	67	12	3789.5	0.38	0	2.22	Pelton	170	155	2.22	1	0.91	20	1.512	0.15	0.0125	5.6069
Highland	Lochan na Cruaiche	172235	777058	171975	778415	0.682	1.0948	0.74349	57	9	2503.9	0.42	0.2	1.53	Pelton	219	206	1.53	0.7	0.41	20	0.686	0.11	0.0194	4.5279
Highland	Allt na Cloiche	181746	759399	181875	760259	0.521	0.8163	0.7421	51	7	2087	0.46	0	1.05	Pelton	178	170	1.05	0.7	0.38	20	0.637	0.14	0.0312	3.7792
Argyll and Bute	Abhainn Strathainn	185094	673366	186194	674116	0.688	1.1869	0.73575	59	9	2632.1	0.44	0.2	1.47	Pelton	158	145	1.47	0.8	0.59	20	1.017	0.19	0.0384	7.1518
Highland	Allt Cailtidh	260107	820258	259557	822000	0.806	1.8451	0.73252	67	12	3609.8	0.51	2.18	2.24	Pelton	160	145	2.24	0.9	0.7	20	1.103	0.34	0.0916	12.333
Renfrewshire	River Calder	233400	661342	235126	659950	0.906	2.5443	0.71974	71	13	4637.4	0.58	6.75	2.66	Pelton	104	95.6	2.66	1.3	1.2	30	3.66	0.72	0.1608	23.596
Highland	Abhainn an Fhasaigh	202079	866327	201137	865596	0.907	1.6951	0.71441	66	11	3365	0.42	1.45	3.15	Pelton	130	121	1.3	1	0.95	20	1.604	0.27	0.0386	9.2704
Highland	Abhainn Coire Mhic Nabuil	187794	858682	186908	857371	1.561	4.1489	0.70885	77	16	7017.3	0.51	13.1	1.8	Pelton	121	112	1.8	1.4	1.77	30	4.397	0.78	0.1235	19.31
Highland	Drundreggan Reservoir	234754	816313	235385	815772	0.539	0.9293	0.70189	55	8	2208.3	0.47	0	1	Pelton	128	120	1	0.8	0.56	20	0.986	0.22	0.0431	9.3095
Highland	Lochan Dubha Ca¹l a' Mhill	188498	853158	188707	854387	1.527	2.6893	0.70145	72	14	4832.3	0.36	6.84	1.55	Pelton	216	204	1.55	1	0.94	15	1.246	0.19	0.0289	6.4255
Highland	Allt Arcabhi	205538	793417	205348	792392	1.567	2.9543	0.68514	74	15	5208.3	0.38	10.9	1.17	Pelton	242	230	1.17	0.9	0.85	15	1.182	0.22	0.044	5.4157

Run-of-River Sites (10% Discount Rate)

County	River	Intake Easting	Intake Northing	Power house Easting	Power house Northing	Power (MW)	Total cost (M£)	NPV (M£)	LEC (£/MWh)	Discounted Payback Period	Energy production (MWh/year)	CF	Line distance (km)	Road distance (km)	Turbine type	Gross Head (m)	Net Head (m)	Penstock Length (km)	Penstock diameter (m)	Qd (m^3s^{-1})	Qd (FDC percentile)	Q10 (m^3s^{-1})	Q50 (m^3s^{-1})	Q90 (m^3s^{-1})	Catchmnet area (km^2)
Highland	Allt Camas a' Choirce	177343	762141	176335	760813	1.03	1.8916	0.68014	68	12	3617.8	0.4	0.2	2.21	Pelton	167	154	2.21	1	0.84	20	1.403	0.18	0.0235	6.6184
Perth and Kinross	Acharn Burn	275869	742202	275603	743719	0.977	2.0349	0.67539	69	13	3825.8	0.45	5.13	1.73	Pelton	206	188	1.73	0.8	0.65	20	1.241	0.22	0.0383	12.589
Highland	Abhainn Dheabhag	226740	822524	227636	823850	1.107	3.121	0.668	75	15	5437.6	0.56	7.8	3.0	Pelton	102	96.1	1.9	1.4	1.46	30	3.864	0.82	0.1544	30
Highland	Loch Fa¨ith an Leathaid	217654	922949	215585	924098	1.043	2.8157	0.66614	74	14	4979.3	0.55	6.51	3.52	Pelton	178	164	2.75	1	0.8	25	1.495	0.44	0.1062	12.719
Highland	Loch na Sa¹iteig	188954	847913	187600	846849	0.798	1.9045	0.66258	69	12	3616.4	0.52	0.77	3.22	Pelton	104	96.6	1.94	1.2	1.04	30	2.657	0.46	0.0828	10.127
Highland	Dubh Lighe	194450	781673	193320	780382	0.922	2.1407	0.66191	70	13	3967.9	0.49	0.2	2.05	Francis	98.9	92	2.05	1.3	1.23	35	4.187	0.52	0.0209	13.738
Highland	Lochan Odhar	275310	799234	275412	799450	0.811	2.8993	0.64547	74	15	5079.8	0.72	0.28	0.46	Kaplan	10.4	9.47	0.26	3	10.2	50	46.61	11.5	2.3156	532.56
Highland	Abhainn an Lain	232956	941517	231480	942123	1.083	2.6143	0.64018	73	14	4648.6	0.49	1.98	2.94	Pelton	120	107	2.34	1.2	1.28	25	2.603	0.5	0.0872	14.003
Highland	Allt an Fhaing	184784	759750	184833	760622	0.504	0.8001	0.63993	54	8	1943.1	0.44	0.4	1.07	Pelton	220	210	1.07	0.6	0.29	20	0.516	0.1	0.0239	2.447
Highland	Allt Chna imhean	203627	863552	202999	863305	0.583	0.8293	0.63667	54	8	1982.8	0.39	0.2	1.36	Pelton	190	176	0.79	0.6	0.41	15	0.567	0.11	0.0212	3.8881
Highland	Allt Coire Shaile	212920	842357	212696	841404	1.791	3.2008	0.62795	76	15	5508.8	0.35	8.79	8.14	Pelton	190	181	1.1	1.1	1.25	15	1.626	0.23	0.0312	6.1969
Argyll and Bute	Abhainn Doire Dhubhaig	149868	734202	149145	735838	0.736	1.3893	0.62457	64	11	2803.6	0.43	0.68	2.02	Pelton	200	171	2.02	0.7	0.53	20	0.865	0.15	0.0222	5.2384
North Ayrshire	Garbh Allt	197469	638380	198337	638676	1.036	1.6014	0.61707	67	12	3111.1	0.34	2.4	3.23	Pelton	200	187	1.02	0.8	0.69	15	0.919	0.11	0.0174	4.6422
Stirling	Keltie Water	263978	710055	265052	707931	0.768	2.381	0.60709	73	14	4261.9	0.63	1.17	3.01	Pelton	103	91.2	3.01	1.2	1.06	40	5.003	0.76	0.1228	31.36
Highland	Allt nan Carnan	188374	841630	189843	841072	0.682	1.3025	0.60297	64	11	2648.9	0.44	0	2.95	Pelton	170	156	1.9	0.8	0.55	20	0.935	0.18	0.0396	4.3316
Highland	Lochan na Craoibhe	170683	786537	169525	785264	0.717	1.3091	0.59968	64	11	2654.9	0.42	0.2	2.09	Pelton	210	187	2.09	0.7	0.48	20	0.835	0.13	0.0261	4.3836
Highland	Allt an Eilein Ghuirm	239889	870803	239809	869409	0.633	1.765	0.571	70	13	3301.6	0.6	0.0	1.6	Francis	65.8	59.8	1.6	1.3	1.31	35	3.528	0.93	0.1847	37
Highland	Loch Garraidh Mhair	217490	891020	216576	890603	0.493	0.8028	0.57083	56	8	1866.1	0.43	0.28	1.13	Pelton	209	198	1.13	0.6	0.31	15	0.408	0.11	0.0288	3.5632
Highland	Allt a' Mhadaidh	222560	874560	223663	875428	0.688	1.5299	0.56323	68	12	2941.5	0.49	0.57	2.01	Pelton	102	94.8	1.61	1.1	0.91	25	1.845	0.38	0.0761	9.4994
Highland	Loch Ard a' Phuill	169868	773366	170055	772829	0.406	0.6219	0.54958	52	7	1571.4	0.44	0.2	0.64	Pelton	168	162	0.64	0.6	0.31	20	0.511	0.1	0.0185	2.8426
Stirling	Allt Gleann a' Chlachain	236546	731000	235398	729095	1.64	3.2177	0.53236	77	16	5421.9	0.38	3.39	2.67	Pelton	169	152	2.67	1.2	1.36	20	2.348	0.2	0.018	8.0362
Highland	Loch Beag	263609	885751	264322	886530	0.458	0.943	0.528	61	10	2025.2	0.5	0.0	1.2	Pelton	103	97.8	1.2	0.9	0.58	20	0.899	0.27	0.0472	16
Argyll and Bute	Abhainn na h-Uamha	151775	735815	150720	736805	0.691	1.1824	0.52326	65	11	2376.3	0.39	0	1.63	Pelton	176	164	1.63	0.8	0.52	20	0.873	0.1	0.0124	4.5098
Highland	Allt Ladaidh	222949	800298	223359	801423	1.107	2.4048	0.51693	75	15	4191.7	0.43	3.33	1.89	Pelton	100	95.4	1.49	1.4	1.47	20	2.586	0.46	0.0787	15.767
Argyll and Bute	Loch Airigh na Creige	201148	703717	202145	702457	0.644	1.1835	0.51403	65	11	2367.2	0.42	0.4	2.09	Pelton	229	216	1.89	0.7	0.37	20	0.69	0.11	0.0274	3.6901
Highland	Allt Raon a' Chroisg	218362	889551	217229	889934	0.499	0.8716	0.50907	60	9	1896.3	0.43	0	1.66	Pelton	203	186	1.46	0.6	0.33	20	0.605	0.1	0.019	3.8279
Highland	River Rha	140406	865336	139455	864162	0.487	1.1833	0.50897	65	11	2361	0.55	0.77	1.65	Pelton	122	110	1.65	0.8	0.55	25	1.009	0.3	0.0685	10.9
Argyll and Bute	Allt na Cuile Riabhaiche	206581	720441	206588	720979	0.433	0.6726	0.50523	55	8	1595	0.42	0.2	0.84	Pelton	152	143	0.64	0.6	0.37	20	0.696	0.11	0.0262	3.3013
Highland	Abhainn a' Choire	236743	926405	236493	925638	0.407	0.770	0.478	59	9	1708.8	0.48	1.1	0.9	Pelton	174	165	0.9	0.6	0.3	20	0.538	0.13	0.0319	3
Highland	Loch a' Bhainne	227519	804209	227849	803138	0.421	0.8065	0.47365	60	9	1757.7	0.48	0.4	1.63	Pelton	167	152	1.23	0.6	0.34	20	0.565	0.14	0.0323	4.9378
Highland	Allt Leacachain	223874	877292	223253	876201	0.518	0.9294	0.47073	62	10	1937.6	0.43	0.28	1.38	Pelton	179	169	1.38	0.7	0.38	20	0.687	0.12	0.0241	4.4868
Highland	Allt Coir' a' Chliabhain	233270	876386	234198	876166	0.874	1.4257	0.46803	69	13	2674.4	0.35	1.65	2.43	Pelton	180	173	1.1	0.9	0.63	15	0.852	0.12	0.0246	4.6586
South Lanarkshire	Stonebyres Falls	289569	645630	288434	645672	0.54	1.94	0.46245	74	14	3434.8	0.73	1.6	1.68	Francis	54.9	52.2	1.48	1.5	1.29	55	4.694	1.62	0.2367	108.09
Perth and Kinross	Allt Fearna	245918	755643	246625	756509	0.44	1.5491	0.45517	71	13	2843.4	0.74	0.88	1.69	Francis	49.9	45.7	1.29	1.3	1.21	55	5.605	1.59	0.3152	49.877
Highland	Allt Choille-rais	220538	776035	220558	777134	1.72	2.7177	0.44899	77	16	4578.8	0.3	8.4	1.43	Pelton	271	247	1.23	0.8	0.88	10	0.88	0.11	0.0055	3.9718
Highland	Abhainn Righ	204217	762737	203049	762957	0.841	1.6766	0.44899	72	14	3026.3	0.41	0	2.62	Pelton	100	93.8	1.52	1.2	1.13	25	2.65	0.21	0.0248	15.069
Highland	Allt a' Mha¨il	204559	802931	204105	802235	0.94	1.5383	0.44866	71	13	2819.7	0.34	3.08	0.92	Pelton	173	167	0.92	0.9	0.7	15	0.927	0.1	0.0083	3.3142
Highland	Allt Coire Mhuilidh	235079	865449	235399	863965	0.467	1.006	0.441	65	11	2017.6	0.49	0.2	1.7	Pelton	150	135	1.7	0.7	0.43	20	0.691	0.19	0.0409	7
Highland	Loch Coire Chuir	250330	785988	249816	787146	0.679	1.6569	0.44017	72	14	2986.6	0.5	0.88	1.59	Francis	88.7	79.7	1.59	1.1	1.05	30	3.146	0.48	0.0747	24.847
Highland	Achriesgill Water	226761	952880	225616	952550	0.447	1.0503	0.43799	66	11	2079.4	0.53	0.48	1.4	Pelton	105	98.6	1.4	0.9	0.56	25	1.059	0.29	0.059	10.131

Run-of-River Sites (10% Discount Rate)

County	River	Intake Easting	Intake Northing	Power house Easting	Power house Northing	Power (MW)	Total cost (M£)	NPV (M£)	LEC (£/MWh)	Discounted Payback Period	Energy production (MWh/year)	CF	Line distance (km)	Road distance (km)	Turbine type	Gross Head (m)	Net Head (m)	Penstock Length (km)	Penstock diameter (m)	Qd (m^3s^{-1})	Qd (FDC percentile)	Q10 (m^3s^{-1})	Q50 (m^3s^{-1})	Q90 (m^3s^{-1})	Catchmnet area (km^2)
Highland	Allt Gharagain	212987	852237	212799	854069	0.705	1.445	0.413	71	13	2638.8	0.43	0.8	2.1	Pelton	169	151	2.1	0.8	0.58	20	1.048	0.17	0.0295	7
South Ayrshire	Water of Fail	239072	623508	238813	623211	0.91	3.4491	0.40309	80	18	5615.5	0.7	1.08	0.68	Kaplan	12.6	11	0.48	3	9.84	50	33.84	10.6	1.5727	571.27
Highland	Allt a' Ghiubhais	187335	782270	187446	781669	0.369	0.6994	0.39762	60	10	1509	0.47	0.2	0.68	Pelton	98.7	94.7	0.68	0.8	0.48	30	1.352	0.15	0.0148	5.6714
Highland	Allt Mar	264091	823131	262781	824481	0.49	1.1787	0.39631	69	12	2222	0.52	1.13	2.1	Pelton	181	167	2.1	0.7	0.36	20	0.558	0.19	0.0496	7.2099
Highland	Allt Dubh Ca¹il na Creige	248353	809974	247598	811802	0.655	1.8834	0.39617	75	15	3272.8	0.57	1.17	2.59	Pelton	100	90.1	2.39	1.1	0.91	30	2.24	0.53	0.1224	20.133
Stirling	Waltersmuir Resr	277901	702076	277651	701822	0.818	2.6379	0.38955	78	17	4390.1	0.61	0.2	0.7	Francis	24.8	23.6	0.7	2.5	4.53	40	11.96	3.73	0.6144	180.41
Highland	Allt Eiteachan	257618	887700	260452	889514	0.601	1.877	0.388	75	15	3253.5	0.62	0.0	4.1	Pelton	169	139	4.1	0.8	0.54	30	1.108	0.35	0.0762	15
Argyll and Bute	Allt Dubh	185284	677586	185945	677186	0.463	0.7916	0.3773	63	11	1622.5	0.4	0.2	0.87	Pelton	138	129	0.87	0.7	0.44	20	0.77	0.1	0.0225	4.2907
Stirling	Allt a' Choire Ghlais	254214	735132	254355	735066	0.9	2.2646	0.37284	77	16	3813.9	0.48	0.28	0.18	Francis	20	19.4	0.18	2.5	6.2	35	22.46	3.16	0.4986	112.01
Dumfries and Galloway	Archer Beck	337564	580553	337427	580406	0.738	2.814	0.3725	79	17	4632.7	0.72	1.25	0.44	Kaplan	10.1	9.37	0.24	3	9.43	50	40.6	10.4	1.9307	466.57
Argyll and Bute	Kilduskland Resr	183879	686603	185162	686543	0.39	0.8272	0.37129	65	11	1668.6	0.49	0.2	1.65	Pelton	171	154	1.65	0.6	0.31	20	0.566	0.13	0.0281	3.4115
Highland	Craig River	178791	863593	176943	863885	1.411	3.8929	0.37023	81	19	6238.9	0.5	10.7	6.53	Pelton	140	124	2.3	1.2	1.44	20	2.236	0.66	0.1539	17.446
Highland	Allt Achaidh Luachraich	225683	804844	225563	803509	0.373	0.8603	0.36869	65	11	1714.9	0.52	0.4	2	Pelton	178	162	1.8	0.6	0.28	25	0.615	0.14	0.0319	4.4811
Highland	Loch Eas na Maoile	238690	933679	238403	933054	0.603	1.472	0.354	73	14	2610	0.49	0.3	0.8	Francis	50.5	48.5	0.8	1.5	1.55	30	3.853	0.76	0.1475	22
Highland	Allt Daingean	224130	804210	224339	802870	0.347	0.7808	0.35208	64	11	1577	0.52	0	1.68	Pelton	159	143	1.68	0.6	0.3	25	0.706	0.14	0.0293	5.0985
Highland	Aldernaig Burn	229618	801952	229768	801039	0.237	0.6808	0.35078	62	10	1426.3	0.69	0	1.03	Pelton	67.6	61.7	1.03	0.8	0.48	45	1.862	0.46	0.0947	17.801
Highland	Loch Ness	244218	813900	243823	814589	0.621	1.4375	0.34851	73	14	2551.9	0.47	3.66	4.83	Pelton	181	176	0.99	0.8	0.44	20	0.732	0.18	0.0297	9.6938
Highland	Meeting of Three Waters	218264	756237	216990	756547	1.335	2.789	0.34556	80	18	4563.8	0.39	5.17	1.97	Pelton	120	106	1.57	1.2	1.6	20	2.711	0.29	0.0209	10.772
Highland	Allt Mar na Sraine	144629	830609	144825	831406	0.301	0.6152	0.34322	61	10	1319.6	0.5	0.2	1.12	Pelton	141	134	0.92	0.6	0.28	20	0.454	0.13	0.028	2.4016
Highland	Abhainn Bhuachaig	191689	844112	192264	842844	0.594	1.3233	0.34197	73	14	2374	0.46	0.2	2.21	Pelton	140	121	2.01	0.8	0.61	25	1.328	0.18	0.0311	5.6689
Highland	Loch na Plangaid	241770	842504	241304	841428	0.314	0.8167	0.33427	66	11	1609.6	0.59	0	1.36	Pelton	90.6	83.1	1.36	0.8	0.47	30	1.036	0.28	0.0485	12.137
Highland	Allt Choire a' Bhalachain	212023	798993	228096	838597	0.524	1.5051	0.32756	75	15	2628.2	0.57	0.68	2.57	Pelton	102	92.5	2.17	1	0.71	30	1.762	0.42	0.0941	9.7438
Highland	Allt Seanabhaile	239440	826730	240808	829657	0.995	2.6902	0.32139	80	18	4388.2	0.5	5.37	3.94	Pelton	302	258	3.94	0.7	0.48	20	0.778	0.21	0.0455	9.5796
Highland	Loch Farr	271592	830924	268995	831447	0.466	1.4551	0.3193	74	15	2544	0.62	1.41	3.13	Pelton	177	156	3.13	0.7	0.37	30	0.747	0.26	0.0621	13.962
Highland	Loch na Maine Beag	220455	861290	221067	860557	0.315	0.647	0.316	63	10	1334.7	0.48	0.0	1.3	Pelton	142	132	1.1	0.6	0.29	20	0.47	0.13	0.0305	5
Highland	Allt a' Bhealaich Mhair	242623	866716	241201	867334	0.359	0.775	0.310	66	11	1518.9	0.48	0.0	1.7	Pelton	176	162	1.7	0.6	0.27	25	0.611	0.1	0.0187	7
Perth and Kinross	Allt Caochan an t-Seilich	255608	759492	254515	758168	0.424	1.2177	0.30945	73	14	2178.5	0.59	0.2	2.08	Pelton	100	90.1	2.08	0.9	0.59	30	1.322	0.35	0.0639	18.375
Highland	Lochan Lice	248741	880115	249890	878446	0.871	3.5223	0.30764	82	19	5612.8	0.74	10.5	2.72	Pelton	101	91.9	2.72	1.3	1.2	50	4.609	1.41	0.3589	43.698
Highland	Allt Ba n	196147	806881	195312	806505	1.941	3.6814	0.30635	82	20	5848.6	0.34	13.5	1.12	Pelton	179	167	1.12	1.1	1.48	15	1.943	0.21	0.0063	7.2198
Perth and Kinross	Allt Coire Cruach Sneachda	266663	755306	267329	757435	0.678	1.623	0.30504	76	16	2777.6	0.47	1.4	2.52	Pelton	169	148	2.52	0.8	0.57	25	1.629	0.18	0.0316	15.14
Perth and Kinross	Allt a' Chobhair	262519	745299	262609	746827	2.021	3.5072	0.30332	82	19	5585.3	0.32	8.49	1.8	Pelton	201	183	1.8	1.1	1.4	15	1.895	0.11	0.0057	10.376
Highland	Allt Cheanna Mhuir	210578	792612	210528	791469	1.086	2.4372	0.30312	80	18	3989.5	0.42	10	1.28	Pelton	251	229	1.28	0.7	0.59	15	0.83	0.19	0.0427	4.3533
Scottish Borders	Whiteadder Water	381582	656255	381861	656085	0.612	1.9554	0.30234	78	17	3270.1	0.61	0.4	0.63	Francis	21.8	21.4	0.35	2.5	3.8	40	9.537	3.15	0.4745	272.43
Highland	River Rha	140703	863557	139869	863781	0.223	0.7172	0.3002	66	11	1421.3	0.73	0.57	0.96	Pelton	62.8	57.1	0.96	0.8	0.49	50	2.121	0.55	0.1107	18.45
Highland	Allt Innis a' Mhuilt	222036	837176	222673	838400	0.522	1.061	0.297	72	13	1931.1	0.42	0.5	1.6	Pelton	155	137	1.6	0.7	0.47	20	0.911	0.13	0.0209	4
Highland	Allt Coire nam Bra than	233056	838983	233216	839457	0.292	0.611	0.294	63	10	1255.6	0.49	0.4	0.8	Pelton	91.9	87.1	0.6	0.7	0.42	25	0.966	0.17	0.0219	11
Highland	Allt Choimhlidh	224219	775632	223717	777174	2.053	3.8987	0.28531	83	20	6147.9	0.34	11.6	1.77	Pelton	211	201	1.77	1.2	1.29	15	1.729	0.19	0.0134	6.607
Highland	Lochan Tain Mhic Dhughaill	183880	785925	183311	785196	0.856	1.6689	0.28434	77	16	2821.9	0.38	3.7	9.04	Pelton	262	240	1.06	0.6	0.44	15	0.592	0.1	0.0186	2.6287
Highland	Allt Coire Mhuilidh	233259	864416	233139	863324	0.265	0.626	0.255	66	11	1232.2	0.53	0.0	1.2	Pelton	129	119	1.2	0.6	0.27	25	0.53	0.14	0.0303	6
Stirling	Allt Leacachan	262508	727537	261698	724995	0.772	2.2053	0.25298	80	18	3585	0.53	3.28	3.06	Pelton	169	152	3.06	0.9	0.63	25	1.479	0.3	0.0506	13.02

Run-of-River Sites (10% Discount Rate)

County	River	Intake Easting	Intake Northing	Power house Easting	Power house Northing	Power (MW)	Total cost (M£)	NPV (M£)	LEC (£/MWh)	Discounted Payback Period	Energy production (MWh/year)	CF	Line distance (km)	Road distance (km)	Turbine type	Gross Head (m)	Net Head (m)	Penstock Length (km)	Penstock diameter (m)	Qd (m^3s^{-1})	Qd (FDC percentile)	Q10 (m^3s^{-1})	Q50 (m^3s^{-1})	Q90 (m^3s^{-1})	Catchmnet area (km^2)
Highland	Allt Horn	231888	942934	231263	942597	0.547	1.1576	0.23935	75	15	2006.7	0.42	1.98	1.41	Pelton	114	105	0.84	0.8	0.65	20	1.114	0.18	0.0304	6.552
Highland	Allt Garbh	245158	839082	245593	840033	0.283	0.717	0.228	70	13	1335.7	0.54	0.2	1.4	Pelton	99.2	90.3	1.2	0.7	0.39	25	0.78	0.19	0.0255	12
Highland	Lochan Fa¨ith an Leathaid	228982	929040	227218	930504	1.648	3.6371	0.22413	83	21	5686.1	0.39	8.49	12.7	Pelton	259	232	2.47	0.9	0.89	15	1.189	0.24	0.0486	5.9393
Argyll and Bute	Allt Easach	206316	741416	206983	739519	1.681	3.69	0.22378	83	21	5764.7	0.39	8.32	2.73	Pelton	158	139	2.33	1.2	1.53	20	2.595	0.29	0.0425	7.6816
Highland	River Beauly	248458	849224	249625	850131	0.271	0.646	0.221	69	12	1222.1	0.51	0.0	1.9	Pelton	171	150	1.7	0.5	0.22	20	0.34	0.1	0.0178	6
Moray	Allt na Ha	316987	828709	317528	829113	1.103	4.1191	0.21933	84	21	6399.2	0.66	4.28	0.87	Francis	22.9	20.9	0.87	2.8	6.98	45	22.53	7.1	1.6888	360.61
Highland	River Glass	255481	868464	255810	868286	0.475	1.770	0.217	80	18	2893.4	0.7	3.7	1.0	Francis	41.1	38.2	0.8	1.4	1.58	50	7.416	1.77	0.3539	77
Perth and Kinross	Spout Rolla	274893	729140	274188	727561	0.486	1.0888	0.21597	76	15	1876.7	0.44	0.57	2.01	Pelton	181	169	2.01	0.7	0.35	25	1.002	0.1	0.0178	6.0108
Na h-Eileanan an Iar	Lochan Tana	137998	915857	137642	915438	1.312	3.7527	0.21594	84	21	5849	0.51	7.84	0.88	Francis	49.6	48.8	0.88	2.5	3.33	25	5.499	1.89	0.3992	79.714
Na h-Eileanan an Iar	Abhainn Eadarra	113089	905217	113022	904169	0.253	0.7465	0.21525	71	13	1365.5	0.62	0	1.22	Pelton	71.4	64	1.22	0.8	0.49	40	1.691	0.36	0.0638	10.446
Highland	Allt Mar Gisgil	218302	941760	217452	941729	0.892	2.4339	0.21385	82	19	3879.9	0.5	8.32	1.58	Pelton	100	97.2	1.01	1.3	1.16	20	1.82	0.54	0.1229	19.893
Highland	Loch Dubh a' Chuail	235013	926853	236124	925881	0.486	1.110	0.205	76	16	1895.8	0.45	1.6	2.2	Pelton	207	188	1.8	0.6	0.32	20	0.566	0.11	0.0246	2
Highland	Lan Mar	144139	852211	143588	851398	0.289	0.7917	0.20474	73	14	1420.4	0.56	0.2	1.47	Pelton	81.7	74.8	1.19	0.8	0.48	30	1.184	0.26	0.0521	8.1047
Highland	Loch Aline	168257	746556	168595	746328	0.2	0.4154	0.20445	63	10	858.99	0.49	0	0.45	Pelton	89.9	86	0.45	0.6	0.29	20	0.443	0.13	0.0252	3.7828
Highland	Allt Cailtidh	261562	820594	260783	823212	0.602	1.8414	0.20337	80	18	2984.2	0.57	1.57	3.89	Pelton	180	161	3.49	0.8	0.46	25	0.839	0.28	0.0748	10.568
Perth and Kinross	Loch Moraig	287668	766521	287620	766381	0.777	2.5106	0.20104	82	20	3979.2	0.58	5.08	0.16	Francis	21.1	20.8	0.16	2.5	4.97	40	21.08	4	0.902	234.71
Highland	Allt Meallan Gobhar	183305	844659	184049	844066	0.659	1.54	0.20068	79	18	2531.6	0.44	3.31	1.22	Pelton	124	115	1.22	0.9	0.71	20	1.15	0.23	0.0387	5.5999
Highland	River Attadale	194359	837182	194251	837809	0.201	0.4566	0.19997	65	11	915.18	0.52	0	0.74	Pelton	104	98.7	0.74	0.6	0.25	25	0.533	0.12	0.0224	4.5353
Highland	Allt na Cailliche	227244	799914	227699	800403	0.276	0.6342	0.19673	70	13	1176.3	0.49	0.4	0.84	Pelton	101	95.3	0.84	0.7	0.36	25	0.783	0.14	0.0247	4.7218
Argyll and Bute	Loch na Ba¨iste	176615	654986	176645	656041	0.269	0.7783	0.19451	73	14	1388.5	0.59	0.2	1.26	Pelton	80	73.4	1.26	0.8	0.45	30	0.84	0.28	0.0445	12.225
Perth and Kinross	Allt Odhar	273924	747817	273629	747015	0.293	0.6365	0.19395	70	13	1176.4	0.46	0.2	0.96	Pelton	121	110	0.96	0.6	0.33	25	0.915	0.1	0.014	9.3463
Argyll and Bute	Uisge Fealasgaig	152554	725236	151889	726411	0.359	1.0629	0.19363	76	16	1811.9	0.58	1.61	1.47	Pelton	98.7	89.5	1.47	0.8	0.5	30	1.149	0.29	0.0534	8.6107
Stirling	River Dochart	251499	731092	251249	729666	0.737	1.6435	0.18376	80	18	2666.1	0.41	4.2	1.89	Pelton	215	197	1.69	0.7	0.46	20	0.9	0.13	0.0267	5.5693
Highland	Allt Dail a' Chuirn	230246	806372	231344	805674	0.538	1.2113	0.1815	78	17	2018.9	0.43	2.28	3.66	Pelton	210	192	1.46	0.6	0.35	15	0.465	0.12	0.0288	2.5192
Highland	Allt Iarairidh	231678	814979	232428	814439	0.25	0.6128	0.18009	71	13	1124.8	0.51	0	1.3	Pelton	110	105	1.1	0.7	0.29	25	0.678	0.14	0.0267	4.741
Highland	Inverianvie River	196045	888599	195298	889610	0.994	2.5507	0.17914	83	20	4013.4	0.46	7.58	1.55	Pelton	114	104	1.35	1.1	1.21	20	1.972	0.44	0.0842	15.967
Highland	Lochan a' Chreobhair	231623	939949	230780	940763	0.275	0.7832	0.17874	74	15	1377.3	0.57	0.6	2.08	Pelton	99.8	91.1	1.28	0.7	0.37	30	0.899	0.22	0.044	8.6566
Argyll and Bute	Allt Chaluim	224186	721537	224629	720814	1.468	3.162	0.17869	84	21	4924.5	0.38	8.61	4.34	Pelton	113	105	1.09	1.3	1.78	20	3.143	0.33	0.0618	13.896
Perth and Kinross	Falls of Barvick	284550	725554	284996	724189	0.482	1.0885	0.17652	77	16	1829.9	0.43	1.37	1.79	Pelton	198	176	1.79	0.6	0.34	20	0.65	0.1	0.0182	7.476
Argyll and Bute	Allt Gleann Laoigh	205976	686544	205642	686160	0.474	0.9049	0.17473	76	16	1554.1	0.37	0.57	3.12	Pelton	101	98	0.54	0.9	0.6	20	1.05	0.1	0.018	5.1669
Perth and Kinross	Allt a' Chreagain Odhair	261164	760017	260968	759284	0.179	0.6214	0.17416	72	13	1130.7	0.72	0	1.13	Pelton	52.6	50	0.93	0.9	0.44	50	1.712	0.49	0.0866	11.665
Highland	Lochan nam Breac	237279	864329	237199	863600	0.193	0.479	0.171	68	12	914.01	0.54	0.2	1.0	Pelton	122	112	0.8	0.5	0.21	25	0.404	0.11	0.0198	6
Highland	Allt an Eas Bha in Mhair	216500	837515	217722	837906	0.535	1.282	0.170	79	17	2110.1	0.45	0.9	1.5	Pelton	100	94.1	1.5	1	0.71	25	1.629	0.21	0.0324	9
Highland	Allt Tigh Na¨ill	274203	898618	275370	898870	0.52	1.738	0.169	81	19	2788.7	0.61	1.3	1.5	Francis	60.2	52.5	1.5	1.2	1.24	35	2.731	0.91	0.1538	51
Highland	Allt Coire na Faochaige	220482	840797	220158	840203	0.28	0.6375	0.16668	72	14	1146	0.47	0.4	0.74	Pelton	88.6	82.1	0.74	0.7	0.42	30	1.304	0.13	0.0134	6.9401
Highland	Loch na Ba¨iste	238281	841786	238606	841190	0.246	0.5554	0.16607	71	13	1022.8	0.47	0	0.89	Pelton	110	107	0.89	0.7	0.28	25	0.73	0.11	0.0176	4.8485
Highland	Kinlochewe River	200598	862635	201805	863204	0.325	0.7799	0.16355	75	15	1354.7	0.48	0.4	1.49	Pelton	145	129	1.49	0.6	0.31	25	0.743	0.11	0.0231	3.9321
Highland	Allt an Fhaing	191854	777008	192411	778095	0.541	1.2169	0.16036	79	17	2002.5	0.42	0.8	1.61	Pelton	107	102	1.33	1	0.66	25	1.415	0.15	0.0132	5.3995
Highland	River Brora	291104	908460	291984	907539	0.193	0.559	0.160	71	13	1021.1	0.61	0.0	1.7	Pelton	132	116	1.5	0.5	0.2	30	0.417	0.13	0.0217	8
Highland	Loch Arienas	169360	752534	168884	751398	0.416	0.9888	0.15923	77	16	1661.1	0.46	1.33	2.67	Pelton	160	139	1.42	0.6	0.37	20	0.599	0.12	0.0237	3.9394

Run-of-River Sites (10% Discount Rate)

County	River	Intake Easting	Intake Northing	Power house Easting	Power house Northing	Power (MW)	Total cost (M£)	NPV (M£)	LEC (£/MWh)	Discounted Payback Period	Energy production (MWh/year)	CF	Line distance (km)	Road distance (km)	Turbine type	Gross Head (m)	Net Head (m)	Penstock Length (km)	Penstock diameter (m)	Qd (m^3s^{-1})	Qd (FDC percentile)	Q10 (m^3s^{-1})	Q50 (m^3s^{-1})	Q90 (m^3s^{-1})	Catchmnet area (km^2)
North Ayrshire	Garbh Allt	194129	636350	193975	635266	0.189	0.5164	0.15471	71	13	951.41	0.58	0	1.29	Pelton	130	116	1.29	0.5	0.2	30	0.561	0.11	0.0211	3.9745
Argyll and Bute	Allt a' Chapuill	202349	681491	201832	681509	0.167	0.4852	0.1469	71	13	895.6	0.61	0	0.59	Pelton	50.4	47.6	0.59	0.8	0.43	35	1.753	0.29	0.055	10.69
Highland	Allt Coire na Maine	283375	901411	283844	900960	0.205	0.633	0.145	74	15	1114	0.62	0.0	1.1	Pelton	57.3	54.6	0.9	0.9	0.46	35	1.096	0.33	0.0491	23
Highland	Allt a' Choire Dhuibh	189207	781188	189946	780578	0.66	1.625	0.14468	82	19	2592.7	0.45	0.4	1.09	Francis	61.5	56.4	1.09	1.3	1.45	30	3.874	0.46	0.0395	13.872
Argyll and Bute	Allt a' Ghlinne Dhuibh	153425	730997	153661	729799	0.379	0.87	0.14465	77	16	1466.9	0.44	0	1.67	Pelton	119	105	1.39	0.7	0.45	25	0.903	0.12	0.008	2.3034
North Ayrshire	Allt Mar	199396	631036	200824	630836	0.374	0.8996	0.14096	78	17	1506.6	0.46	0.8	2.21	Pelton	178	163	1.73	0.6	0.28	20	0.51	0.11	0.0257	3.3758
Highland	Allt Bad an Fhliuchaidh	226420	859577	227169	860405	0.299	1.032	0.137	79	17	1699.2	0.65	1.2	2.8	Pelton	89.7	81.2	1.6	0.8	0.46	40	1.656	0.36	0.0625	14
Highland	Allt Taige	217856	832208	218696	831141	1.107	2.081	0.136	83	21	3261.7	0.34	4.1	4.9	Pelton	223	214	1.5	0.9	0.65	15	0.888	0.1	0.017	4
Highland	Loch an Ime	171560	822290	170424	823706	0.317	1.0215	0.13409	79	18	1680.4	0.6	0	2.21	Pelton	101	91	2.21	0.8	0.43	35	1.316	0.28	0.0487	9.7449
East Ayrshire	Cessnock Water	253889	626218	253603	626328	0.745	2.3889	0.13214	84	21	3717.1	0.57	3	0.34	Francis	23.4	22.9	0.34	2.5	4.28	35	10.41	3.08	0.4713	158.52
Highland	Easan Dorcha	200411	852672	201568	852628	0.775	1.751	0.13012	82	20	2763.4	0.41	4	1.37	Pelton	138	127	1.37	0.9	0.77	20	1.354	0.19	0.0375	5.8933
Stirling	Lochan a' Craoi	238277	728070	237370	726864	0.879	2.0773	0.12628	83	21	3245.5	0.42	6.42	1.69	Pelton	207	193	1.69	0.8	0.57	20	1.072	0.17	0.0357	5.0181
Stirling	Allt a' Bheithe	275002	704821	275680	703964	0.198	0.7849	0.126	78	16	1318.1	0.76	0	1.69	Pelton	54.5	49.7	1.41	0.9	0.49	55	1.954	0.63	0.1223	21.774
North Ayrshire	Glenashdale Falls	201998	625023	203211	625086	0.243	0.6804	0.12536	76	16	1161.5	0.55	0.57	2.53	Pelton	155	137	1.43	0.5	0.22	25	0.502	0.11	0.0244	3.8982
Highland	Allt nan Carnan	189718	840720	189696	839759	0.33	0.9583	0.12442	79	18	1574.7	0.55	1.2	1.32	Pelton	91	82.9	1.32	0.8	0.49	30	1.28	0.25	0.0544	6.0825
Highland	Allt a' Gharbh Bhaid	243153	867909	241475	867990	0.317	0.798	0.120	78	17	1331.1	0.48	0.0	2.0	Pelton	150	134	1.8	0.6	0.29	25	0.705	0.1	0.014	7
Highland	Caochan Dir na Lair	291543	840625	291744	840695	1.156	4.3638	0.11815	85	23	6645.6	0.66	9.97	0.43	Kaplan	12.9	11.8	0.23	3	11.6	40	30.89	10.3	2.545	469.93
Highland	Allt Goibhre	246126	849885	247829	851313	0.528	1.861	0.115	83	21	2909.3	0.63	1.8	3.0	Pelton	103	90.3	2.8	1	0.73	35	1.848	0.51	0.0886	26
Na h-Eileanan an Iar	Loch an Ruisg	118486	905693	119385	905814	0.25	0.7168	0.11457	78	17	1203.1	0.55	0.28	1.04	Pelton	73.3	67.8	1.04	0.8	0.46	30	1.101	0.24	0.053	5.6835
Highland	River Romesdal	142074	854015	141003	853565	0.218	0.7849	0.11339	78	17	1303.4	0.68	0.48	1.35	Pelton	70	64	1.35	0.8	0.42	45	1.827	0.4	0.0763	13.679
Perth and Kinross	Allt Lairig nan Lunn	244898	740413	245554	741667	0.332	0.8723	0.10566	80	18	1424.6	0.49	0	1.62	Pelton	107	100	1.62	0.8	0.41	30	1.27	0.16	0.0342	5.6486
Highland	Allt na Fuar-ghlaic	273133	839360	272618	839336	0.166	0.5177	0.10562	75	15	895.69	0.62	0	0.75	Pelton	53.4	50.2	0.75	0.8	0.41	30	0.803	0.28	0.0572	15.865
Highland	Loch Bad na Goibhre	210432	921721	209433	922111	0.418	1.4289	0.10221	83	20	2250.5	0.61	0.48	1.33	Francis	55.6	52.7	1.33	1.3	0.99	40	3.267	0.8	0.1559	32.828
Highland	Allt Bail' an Tuim Bhuidhe	228769	814198	228149	812890	0.202	0.619	0.09909	78	17	1039.1	0.59	0.2	1.72	Pelton	141	123	1.72	0.5	0.2	30	0.469	0.12	0.027	4.3757
Highland	Loch Sunart	177669	758783	177815	759556	0.282	0.6435	0.0961	78	17	1072.2	0.43	0.28	0.9	Pelton	99.9	93.8	0.9	0.7	0.37	20	0.624	0.12	0.0207	3.1977
Highland	Dog Falls	237657	789357	236718	791903	1.409	4.0684	0.08755	86	24	6169.3	0.5	11.4	6.36	Pelton	217	193	3.39	1	0.92	25	2.17	0.39	0.0879	13.579
Highland	Alltan Eisg	188428	846487	187657	846386	0.273	0.6663	0.08614	79	18	1094.5	0.46	0.28	2.6	Pelton	114	104	0.87	0.6	0.32	25	0.685	0.1	0.0168	2.9718
Na h-Eileanan an Iar	Loch na Sgeireagan Mar	114226	904096	113608	903634	0.204	0.5158	0.08561	77	16	869.54	0.49	0.2	0.88	Pelton	98.5	91.5	0.88	0.6	0.27	25	0.54	0.11	0.0197	3.4093
Highland	Lochan Dearg	209316	907580	209378	908406	0.486	1.1766	0.08363	83	20	1852.5	0.44	2.24	3.53	Pelton	148	137	1.17	0.7	0.44	20	0.735	0.14	0.0258	4.238
Na h-Eileanan an Iar	Abhainn Giosla	112190	926110	112966	925759	0.184	0.6935	0.08141	80	18	1129.5	0.7	0.4	1	Pelton	50.1	46.8	1	0.9	0.49	45	1.443	0.5	0.1189	15.53
Perth and Kinross	Allt Kinardochy	277371	757062	277799	757723	0.178	0.5306	0.08053	78	17	885.59	0.57	0	1.32	Pelton	86.8	77.2	1.12	0.6	0.28	30	0.74	0.15	0.0157	14.306
Highland	Allt na Cra¬che	176241	750413	174766	750737	0.252	0.826	0.07979	81	19	1325.2	0.6	0	1.84	Pelton	89.6	73.1	1.84	0.7	0.43	35	1.327	0.26	0.0476	6.2449
Perth and Kinross	Castlehill Resr	300188	702983	300519	702993	0.283	0.9388	0.07813	82	20	1491.4	0.6	0.2	0.56	Francis	30.1	28.8	0.36	1.3	1.28	40	6.225	0.98	0.1572	62.653
Argyll and Bute	Eas nam Broighleag	195834	679796	193936	679206	0.256	0.9375	0.07801	82	20	1489.3	0.66	0.2	2.78	Pelton	101	85.3	2.3	0.7	0.37	35	1.383	0.29	0.0647	10.975
Highland	Allt an Eain	225220	810498	225019	811401	0.206	0.5228	0.07605	78	17	868.68	0.48	0	1.04	Pelton	102	93.5	1.04	0.6	0.27	25	0.674	0.1	0.02	2.8373
Highland	Caledonian Canal	266057	839520	265692	840838	0.259	0.8173	0.07548	81	19	1307.2	0.58	0.68	1.64	Pelton	105	96.4	1.64	0.7	0.33	25	0.572	0.2	0.0383	14.617
Highland	Lochan na Creige Duibhe	174365	784859	173936	784391	0.229	0.5696	0.07437	79	18	936.51	0.47	0	0.99	Pelton	70.4	63.4	0.71	0.7	0.45	30	1.255	0.13	0.0133	6.8447
Highland	Fa¨ith Raoicidhdail	195265	761161	195880	760806	0.231	0.5656	0.07246	79	18	928.32	0.46	0	0.79	Pelton	76.9	70.5	0.79	0.7	0.41	30	1.143	0.12	0.012	4.729
Highland	Allt a' Chaorainn	219816	750527	219576	751002	1.625	3.3783	0.07229	86	24	5122.3	0.36	6.26	0.58	Francis	57.1	56.5	0.58	2.5	3.54	20	5.882	0.64	0.0228	21.892
Stirling	Loch Mahaick	269991	705812	269961	704423	0.194	0.6313	0.07057	80	18	1024.1	0.6	0	1.84	Pelton	99.6	86.4	1.64	0.6	0.28	30	0.576	0.17	0.0309	7.2508

Run-of-River Sites (10% Discount Rate)

County	River	Intake Easting	Intake Northing	Power house Easting	Power house Northing	Power (MW)	Total cost (M£)	NPV (M£)	LEC (£/MWh)	Discounted Payback Period	Energy production (MWh/year)	CF	Line distance (km)	Road distance (km)	Turbine type	Gross Head (m)	Net Head (m)	Penstock Length (km)	Penstock diameter (m)	Qd (m^3s^{-1})	Qd (FDC percentile)	Q10 (m^3s^{-1})	Q50 (m^3s^{-1})	Q90 (m^3s^{-1})	Catchmnet area (km^2)
North Ayrshire	Smallburn Resr	230672	657640	231560	656573	0.653	1.8165	0.06128	85	23	2780.5	0.49	3.41	1.89	Pelton	107	101	1.69	1.1	0.81	25	2.011	0.32	0.0773	11.367
Highland	Loch Sgurr na Gaoithe	168311	786546	168033	785930	0.152	0.4232	0.05891	79	17	700.17	0.53	0.2	0.95	Pelton	94.4	85	0.75	0.5	0.22	25	0.462	0.1	0.0203	3.4301
Dumfries and Galloway	Black Water	262293	588546	261085	588527	0.256	1.0421	0.0572	84	21	1621	0.72	18.4	1.68	Pelton	78.8	71.5	1.48	0.8	0.44	50	1.681	0.47	0.0658	22.257
Argyll and Bute	River Ruel	202993	683096	203051	682385	0.145	0.4454	0.05611	79	18	729.95	0.57	0	1.24	Pelton	71	64.9	0.76	0.6	0.27	30	0.895	0.16	0.0312	5.5629
North Ayrshire	Allt nan Calaman	195175	634356	194558	635046	0.187	0.5281	0.05427	81	19	851	0.52	0.28	1.02	Pelton	99.1	92.4	1.02	0.6	0.25	30	0.749	0.1	0.0216	4.3369
Perth and Kinross	Black Water	314629	756614	313919	756512	0.169	0.5202	0.05242	81	19	837.16	0.57	0.57	0.8	Pelton	79.9	73.1	0.8	0.6	0.28	25	0.483	0.16	0.0259	10.739
Perth and Kinross	Allt an Fheadain	249407	755651	249608	756236	0.17	0.6148	0.04723	82	20	972.13	0.65	0.8	0.9	Pelton	50.1	46.5	0.7	0.8	0.45	40	1.635	0.36	0.0555	16.563
Argyll and Bute	Crarae Bay	197765	697997	198493	697490	0.177	0.5377	0.04497	82	20	854.46	0.55	0.2	1.37	Pelton	101	94.1	1.17	0.6	0.23	30	0.73	0.12	0.0269	4.2477
Highland	Allt Beithe	189089	887853	188454	888457	0.191	0.6245	0.04448	83	20	983.32	0.59	0.28	1.34	Pelton	71.4	64.4	1.06	0.7	0.37	30	0.746	0.22	0.046	10.671
Highland	Abhainn Thra il	191914	853929	191188	854898	1.198	3.2669	0.04408	86	24	4923.2	0.47	9.49	1.99	Pelton	100	96.1	1.51	1.5	1.59	25	3.255	0.57	0.1027	18.083
Stirling	Lossburn Resr	284701	697937	284841	696963	0.26	0.7059	0.04314	83	21	1103.1	0.48	0.97	1.09	Pelton	123	114	1.09	0.6	0.28	25	0.723	0.1	0.0107	11.189
Perth and Kinross	Allt a' Chrombaidh	279259	767244	278911	766545	0.284	0.8008	0.04184	84	21	1243.2	0.5	1.81	0.86	Pelton	102	96.5	0.86	0.7	0.36	20	0.541	0.16	0.0265	10.211
Highland	Allt Garbh	139491	847735	140483	848283	0.203	0.6847	0.03977	83	21	1067.6	0.6	0	1.68	Pelton	80.3	71.4	1.48	0.7	0.35	30	0.677	0.23	0.0551	6.4872
Highland	Falls of Pattack	255419	787316	255721	788419	1.224	3.6943	0.0369	87	25	5552	0.52	1.8	1.5	Francis	40.6	38.9	1.3	2.5	3.94	30	9.731	2.24	0.4642	82.734
Highland	Allt an Doire Fhea rna	217409	801945	217569	801612	0.122	0.342	0.02913	82	19	544.15	0.51	0	0.4	Pelton	58.2	55	0.4	0.6	0.27	25	0.576	0.12	0.0218	5.121
Highland	Allt a' Ghlinne	237308	857926	238608	857566	0.19	0.659	0.023	85	23	1008.6	0.61	0.5	1.6	Pelton	100	88.8	1.6	0.6	0.26	35	0.994	0.17	0.0229	11
Highland	River Glass	255610	865516	258937	865576	0.496	2.059	0.020	87	25	3092.4	0.71	0.2	4.1	Pelton	101	82	3.9	1	0.76	45	2.311	0.72	0.1428	37
Perth and Kinross	Allt Eigheach	243548	761721	243568	760517	0.521	1.4182	0.01726	86	24	2134.9	0.47	2.6	1.92	Pelton	100	95	1.32	1	0.69	25	1.738	0.25	0.0552	11.786
North Lanarkshire	East Corrie Resr	271018	679633	271988	678151	0.234	0.7681	0.01453	86	24	1162.4	0.57	0.57	2.25	Pelton	165	140	2.25	0.5	0.2	25	0.483	0.11	0.0185	4.8747
Highland	Abhainn a' Choire	236607	924546	237431	924762	0.119	0.436	0.013	85	23	665.68	0.64	0.0	0.9	Pelton	62.3	55.4	0.9	0.6	0.26	35	0.65	0.2	0.0519	5

Run-of-River Sites (15% Discount Rate)

County	River	Intake Easting	Intake Northing	Power house Easting	Power house Northing	Power (MW)	Total cost (M£)	NPV (M£)	LEC (£/MWh)	Discounted Payback Period	Energy production (MWh/year)	CF	Line distance (km)	Road distance (km)	Turbine type	Gross Head (m)	Net Head (m)	Penstock Length (km)	Penstock diameter (m)	Qd (m^3s^{-1})	Qd (FDC percentile)	Q10 (m^3s^{-1})	Q50 (m^3s^{-1})	Q90 (m^3s^{-1})	Catchmnet area (km^2)
Highland	Abhainn Cuileig	218376	877463	219388	879105	7.092	8.2077	6.55835	50	6	26920	0.43	0.2	2.47	Francis	138.9	131	2.27	2.5	6.56	20	10.56	2.53	0.5415	62.65
Highland	Falls of Kirkaig	211383	917701	209239	918874	6.456	9.5551	6.4871	53	7	29451	0.52	0.6	3.35	Francis	110.7	98.6	2.78	2.6	7.92	25	14.42	4.33	1.0072	136.68
Highland	Allt a' Ghlomaich	201981	825644	200544	826610	4.763	5.7198	4.3586	51	6	18412	0.44	7.92	2.61	Francis	271.3	252	2.41	1.4	2.3	25	4.798	0.76	0.1094	19.619
Perth and Kinross	Allt Coire a' Mhar-fhir	299560	741050	301027	741769	4.953	8.218	3.72676	61	8	22281	0.51	8.41	1.94	Francis	80.8	73.3	1.94	2.7	8.21	25	16.28	4.15	0.6836	205.77
Highland	River Talladale	191678	867281	191857	869736	2.841	4.22	3.37574	50	6	13847	0.56	0.2	3.24	Pelton	210.9	196	2.84	1.4	1.85	30	4.387	1.04	0.2309	19.789
Highland	Allt Seanghail	238968	803549	237911	805996	7.061	9.4648	2.91139	67	10	23389	0.38	2.2	4.65	Francis	160.3	152	3.07	2.5	5.61	15	7.674	1.79	0.4109	58.267
Highland	Loch Cha¹ilean Dubha	206697	867084	207616	864520	2.295	4.262	2.79488	54	7	12974	0.65	3.88	3.17	Pelton	189.1	169	2.97	1.3	1.72	40	5.898	1.4	0.3043	30.164
Highland	Loch Belivat	299562	849298	299707	849347	3.573	6.4894	2.7778	62	9	17322	0.55	7.59	0.38	Kaplan	23.3	20.8	0.18	3	20.2	25	35.42	12.4	3.0325	596.09
Highland	Loch Bad na Goibhre	210119	923410	209599	923080	2.936	4.7204	2.75852	56	7	13815	0.54	1.37	0.68	Francis	44.8	42.4	0.68	2.8	8.56	30	18.7	5.29	1.1897	164.45
Perth and Kinross	Burn of Auchrannie	328407	752842	328499	752844	2.746	3.755	2.698	52	6	11819	0.49	6.6	0.4	Francis	55.8	55.5	0.1	2.5	6.07	25	12.22	3.04	0.5706	174
Perth and Kinross	Falls of Bruar The	282041	768041	282335	765977	1.864	3.485	2.459	53	7	10893	0.67	2.7	2.6	Pelton	161	145	2.6	1.3	1.63	40	5.526	1.4	0.3405	67
Highland	Loch Kirkaig	208306	919330	207972	919340	2.328	3.5506	2.44295	53	7	10997	0.54	0.6	1.48	Francis	42.5	41.6	0.38	2.8	6.93	30	14.74	4.44	1.0225	140.79
Highland	River Glass	258334	866446	259768	866816	3.355	5.3691	2.40438	61	8	14507	0.49	0.2	1.67	Francis	79.6	75.5	1.67	2.5	5.41	25	10.36	2.68	0.5455	116.03
Perth and Kinross	Glendams	317744	749115	317741	749097	4.497	5.9456	2.24304	64	9	15374	0.39	0.88	1.4	Kaplan	23.8	23.5	0.02	3	22.5	15	29.57	7.52	1.2345	433.72
Highland	Allt Coire Eaghainn	217489	768908	215348	768408	7.31	9.5559	2.03307	71	12	22122	0.35	5.05	2.85	Francis	157.5	149	2.85	2.5	5.93	15	7.667	1.19	0.065	31.723
Highland	Abhainn Droma	220910	877640	220110	878223	1.436	2.1998	1.94984	48	6	7531.2	0.6	0	1.11	Pelton	101.7	98.7	1.11	1.6	1.86	35	5.461	1.27	0.275	37.871
Highland	Lochan na Craoibhe-beithe	254419	824658	252056	823948	1.776	3.9973	1.90255	60	8	10985	0.71	3.43	3.56	Pelton	171	154	3.56	1.3	1.46	45	4.693	1.46	0.3314	73.15
Highland	River Lair	198937	850207	200131	848245	2.252	2.8362	1.47828	58	8	8005.7	0.41	0	2.99	Pelton	328.9	292	2.79	0.9	0.97	20	1.665	0.22	0.0351	6.7027
Highland	Lochain a' Mhill Dheirg	231417	932994	229877	933030	2.564	3.9099	1.47659	64	9	10113	0.45	4.81	9.32	Pelton	217.3	206	1.95	1.3	1.58	20	2.628	0.57	0.1242	13.775
Highland	Allt an Ruighe	191775	824494	190612	823105	2.657	3.7982	1.43157	64	9	9819	0.42	6.13	2.05	Pelton	260.5	240	2.05	1.1	1.41	20	2.471	0.39	0.0744	12.185
Perth and Kinross	Burn of Auchrannie	329511	751555	329610	750731	2.27	4.869	1.410	67	10	11887	0.6	6.9	0.9	Francis	47.1	45.5	0.9	2.8	6.17	35	16.19	4.41	0.7891	290
Highland	Allt Briste	226123	935030	224983	934037	2.324	3.8845	1.40698	64	9	9948.2	0.49	6.79	6.34	Pelton	183.8	164	1.84	1.2	1.81	20	2.954	0.76	0.1753	21.633
Highland	Allt a' Chonais	206765	848429	205509	848892	2.294	2.9439	1.40128	60	8	8090.5	0.4	0.77	1.76	Pelton	170.8	163	1.56	1.4	1.79	20	2.942	0.42	0.0441	12.515
Highland	Allt a' Mhuilinn	216086	773054	213917	775674	2.705	3.3077	1.3905	62	9	8787.7	0.37	1.33	3.88	Pelton	476.5	409	3.88	0.8	0.83	15	1.062	0.14	0.0016	3.5073
Highland	Allt Ba n an La¬-ruighe	197883	826084	198421	827001	1.995	2.5581	1.31735	58	8	7194.3	0.41	5.94	1.36	Pelton	326.6	303	1.36	0.8	0.83	15	1.125	0.26	0.055	6.0832
Argyll and Bute	Eagle's Fall	222706	714223	221595	714808	2.361	2.4556	1.30213	58	8	6967.9	0.34	3.38	1.44	Pelton	370	343	1.44	0.8	0.86	15	1.209	0.14	0.0357	5.0617
Highland	Allt Coire na Creiche	186486	761764	185487	760739	1.744	2.1343	1.22916	56	7	6216.6	0.41	0	1.68	Pelton	243.6	220	1.68	0.9	1	20	1.647	0.23	0.0338	5.4508
Highland	Loch Belivat	299958	849634	300007	849754	1.927	4.6827	1.14613	69	11	11087	0.66	7.82	0.14	Kaplan	17.5	16.6	0.14	3	13.7	40	35.4	12.4	3.0344	596.58
Perth and Kinross	Falls of Moness	285065	747188	285540	749129	1.525	2.5106	1.13486	61	8	6800.7	0.51	1.6	2.27	Pelton	201.9	181	2.27	1	1.07	20	1.685	0.47	0.0794	25.479
Highland	Allt Daim	217684	774678	215535	776794	2.998	3.8023	1.13314	67	10	9335.9	0.36	3.35	3.65	Pelton	450.6	407	3.65	0.9	0.93	15	1.211	0.15	0.0025	4.3907
Highland	Loch Kirkaldy	293521	842892	293449	842935	2.086	4.8306	1.10112	70	12	11304	0.62	8.18	0.29	Kaplan	17.3	16.6	0.09	3	14.8	35	33.99	11.8	2.8819	550.55
Highland	Allt Coire an Eich	254778	804701	253608	806602	2.059	4.1711	1.03605	69	11	9900.8	0.55	7.73	3.87	Pelton	208.1	191	2.82	1.2	1.37	25	2.57	0.79	0.2227	24.515
Highland	Abhainn Bra igh Horrisdale	181708	867847	181784	869099	1.336	2.7577	0.9744	65	10	7022.3	0.6	3.55	4.67	Pelton	100.4	95.5	1.42	1.5	1.78	35	4.667	1.23	0.2845	23.598
Argyll and Bute	Garbh-allt Mar	221476	713017	220568	713735	1.666	1.785	0.93451	58	8	5045.2	0.35	1.88	1.4	Pelton	380.7	357	1.4	0.7	0.58	15	0.804	0.1	0.0265	4.1708
Argyll and Bute	Eas an Amair	200794	713126	199616	713445	0.998	1.5852	0.88017	57	7	4563.3	0.52	0.2	1.59	Pelton	173.5	166	1.59	1	0.75	25	1.843	0.38	0.0875	8.8809
Highland	Loch Kirkaldy	293242	843151	293304	843381	1.719	4.5771	0.84777	72	13	10389	0.69	7.7	0.49	Kaplan	19	17.7	0.29	3	11.5	45	33.99	11.8	2.885	551.56
Highland	River E	251646	811979	249525	814331	3.807	8.8006	0.81239	78	16	18629	0.56	0	4.3	Francis	96.2	86.2	4.1	2.5	5.36	30	11.95	3.47	0.9051	114.95
Stirling	Allt Dha¹in Croisg	253754	738017	252985	736342	1.971	2.6345	0.8065	67	10	6503.9	0.38	0	2.35	Pelton	247.8	226	2.15	1	1.1	20	2.132	0.19	0.0322	8.9424
Argyll and Bute	River Shira	214053	713064	212946	713387	0.996	1.4064	0.7916	57	7	4066.1	0.47	0.2	1.35	Pelton	190	172	1.35	0.8	0.72	20	1.383	0.28	0.0657	6.0398

Run-of-River Sites (15% Discount Rate)

County	River	Intake Easting	Intake Northing	Power house Easting	Power house Northing	Power (MW)	Total cost (M£)	NPV (M£)	LEC (£/MWh)	Discounted Payback Period	Energy production (MWh/year)	CF	Line distance (km)	Road distance (km)	Turbine type	Gross Head (m)	Net Head (m)	Penstock Length (km)	Penstock diameter (m)	Qd (m^3s^{-1})	Qd (FDC percentile)	Q10 (m^3s^{-1})	Q50 (m^3s^{-1})	Q90 (m^3s^{-1})	Catchmnet area (km^2)
Highland	Allt na Fa¨ithe Buidhe	194297	832050	194061	831383	1.565	3.4129	0.75017	71	12	7940.5	0.58	0	1.05	Francis	34.6	32.1	0.77	2.5	6.15	40	23.82	4.49	0.8177	131.1
Perth and Kinross	River Garry	279830	765892	280597	765513	1.569	3.9945	0.73296	73	13	9055	0.66	0.77	1.13	Francis	31.3	28.7	0.93	2.7	6.96	45	27.65	6.69	1.4302	281.89
East Ayrshire	Burnock Water	250514	621568	250323	621819	1.231	2.54	0.7219	68	11	6178.9	0.57	0.28	0.53	Francis	29.9	29.1	0.33	2.5	5.4	35	12	3.81	0.5721	204.04
Highland	River Grudie	195909	865427	196391	867089	1.104	2.3879	0.70769	67	10	5856.6	0.61	0.57	2.59	Pelton	101.5	94.8	1.99	1.4	1.48	40	5.434	1.04	0.1679	22.257
Highland	Allt Lochain Buidhe	212103	881511	211921	884763	2.334	5.4696	0.70489	76	15	11907	0.58	6.28	4.54	Pelton	221.2	199	4.54	1.3	1.49	30	3.225	0.92	0.2284	24.815
Highland	Abhainn Chia-aig	218137	790483	217597	788890	2.635	4.5612	0.70268	74	14	10119	0.44	11	1.92	Pelton	189.7	174	1.92	1.3	1.94	25	4.318	0.52	0.0743	19.437
Highland	River E	254637	813629	252198	816272	1.258	2.881	0.692	70	11	6799.8	0.62	0.4	4.7	Pelton	289.9	239	4.7	0.8	0.66	30	1.396	0.45	0.1191	16
Argyll and Bute	An t-Inbhir	201819	715160	200573	715376	1.011	1.5893	0.6844	62	9	4249.1	0.48	0.2	1.62	Pelton	182.6	176	1.62	1	0.72	25	1.76	0.28	0.0646	9.3888
Argyll and Bute	Allt nam Muc	204324	707148	205440	704907	1.368	2.7848	0.64257	70	12	6529.4	0.55	0.2	3.12	Pelton	162.5	137	3.12	1.1	1.26	30	4.041	0.58	0.1406	20.745
Argyll and Bute	Donich Water	221366	701853	220229	701927	1.507	2.0893	0.61321	67	10	5114.4	0.39	0.48	1.38	Pelton	150.4	137	1.38	1.1	1.4	20	2.393	0.25	0.0146	6.5097
Highland	Tollie Bay	186970	878852	186882	878930	1.259	3.4657	0.57161	74	13	7750.4	0.7	0.77	0.32	Kaplan	11.3	10.5	0.12	3	14.3	50	66.8	16.3	3.3932	430.03
Highland	Allt Easgadill	179099	759005	178787	759747	0.513	0.7729	0.56548	52	6	2449.4	0.54	0	0.91	Pelton	177.9	172	0.91	0.7	0.37	25	0.628	0.21	0.0486	4.5444
Highland	Allt Coire na Ba	216697	762739	216574	761987	1.284	1.772	0.52985	67	10	4353.8	0.39	0.48	0.89	Pelton	119.2	109	0.89	1.1	1.5	20	2.495	0.26	0.0083	10.159
Highland	Abhainn na Fa¹irneis	197971	870385	195947	870680	2.205	3.894	0.47424	76	15	8431.7	0.44	7.73	3.35	Pelton	262.9	232	2.58	1	1.2	20	2.001	0.36	0.059	8.7131
Highland	Black Water or Uisge Dubh	200036	837629	200028	836657	2.852	4.6972	0.4709	77	16	10005	0.4	4.2	3.45	Francis	77.1	75.2	1.07	2.5	4.62	20	7.826	1.48	0.2787	36.731
Highland	Allt Raon a' Chroisg	218546	888760	217475	888522	0.644	0.9949	0.46295	60	8	2716.7	0.48	0.2	1.39	Pelton	245.9	228	1.39	0.6	0.35	20	0.573	0.15	0.0341	4.0731
Highland	Allt Coire na Ba	219120	763678	218716	762397	1.266	1.722	0.46025	68	11	4141	0.37	0.57	1.51	Pelton	212.7	199	1.51	0.9	0.8	20	1.365	0.11	0.0005	4.4232
Highland	Allt Airdeasaidh	204763	888562	205313	889713	2.786	4.353	0.44216	77	16	9280.9	0.38	15	1.51	Pelton	286.3	264	1.51	1	1.34	15	1.803	0.33	0.06	12.348
Highland	Allt na Claise Brice	171615	747109	170766	747248	0.922	1.8847	0.44093	70	12	4428.9	0.55	1.33	0.98	Francis	72.2	65.7	0.98	1.3	1.73	30	3.785	1.04	0.2104	28.617
Perth and Kinross	Loch Farleyer	280970	750462	281599	749420	0.734	1.1689	0.4401	64	9	3021	0.47	0.6	1.43	Pelton	208.5	193	1.43	0.7	0.47	20	0.885	0.18	0.0225	14.484
Highland	Allt a' Charnaich	234789	802958	234092	803249	0.73	1.3382	0.43122	66	10	3339.2	0.52	0.48	0.9	Francis	93.6	88.9	0.9	1.1	1.01	30	2.849	0.54	0.0958	23.672
Perth and Kinross	Loch a' Choire	291865	763598	291113	762789	0.836	1.7271	0.42823	69	11	4098.4	0.56	1.88	1.27	Pelton	100.2	95	1.27	1.2	1.11	30	3.029	0.6	0.1022	39.247
Highland	Allt Garaidh Ghualaich	215762	798809	217039	800471	1.084	2.3977	0.42703	73	13	5413.9	0.57	0.77	2.48	Pelton	130.1	110	2.48	1.1	1.24	30	3.22	0.69	0.1501	17.384
Argyll and Bute	River Goil	217529	700097	218517	700197	1.179	1.6329	0.41958	69	11	3899	0.38	0	1.23	Pelton	149	137	1.23	1	1.09	20	1.871	0.17	0.0153	8.4613
Highland	Rogie Falls	244654	858496	244804	857621	1.996	5.501	0.414	79	17	11489	0.66	2.9	1.4	Francis	31.3	28	1.2	3	9.08	45	32.26	8.85	1.9292	317
Highland	Allt Coire nam Bra than	231590	840606	231892	839960	0.71	0.9186	0.38749	62	9	2442.7	0.39	0.2	0.78	Pelton	200.3	192	0.78	0.7	0.46	20	0.846	0.1	0.0207	3.4561
Highland	Allt Uchd Rodha	225676	839583	225729	838563	0.687	1.0732	0.38071	65	9	2735.3	0.45	0	1.3	Pelton	176.9	168	1.3	0.8	0.51	25	1.198	0.17	0.0325	6.9471
Highland	Allt Coire Mhuillidh	227595	839651	228096	838597	0.875	1.3613	0.37816	68	11	3297.1	0.43	0	1.43	Pelton	161.4	151	1.43	0.9	0.73	25	1.692	0.18	0.0219	9.0509
Argyll and Bute	Allt Lairig lanachain	212243	731020	212916	729799	0.93	1.4627	0.37261	69	11	3487.3	0.43	0.2	1.74	Pelton	168.7	157	1.54	0.9	0.74	25	1.537	0.18	0.0024	2.7589
Argyll and Bute	Cladich River	211013	720760	210036	721334	0.712	1.4781	0.35859	70	11	3494.5	0.56	0.2	1.72	Pelton	100.1	92.8	1.52	1.1	0.97	30	3.056	0.53	0.1241	18.471
Highland	River Broom	220150	881987	219456	881390	0.511	0.7408	0.35694	60	8	2043	0.46	0	1	Pelton	224.9	216	1	0.6	0.29	20	0.491	0.11	0.0229	3.2605
Highland	Allt Coire an Eoin	221995	775326	222597	775991	2.431	3.9115	0.34783	78	16	8258.1	0.39	10	1.23	Francis	142	133	1.23	1.4	2.23	20	3.546	0.54	0.0406	13.414
Highland	Loch Garbhaig	189813	870245	189514	871261	0.501	0.8764	0.34515	63	9	2290	0.52	0	1.33	Pelton	173.6	164	1.33	0.7	0.38	25	0.771	0.19	0.0429	5.48
Highland	Allt Gleann a' Mhadaidh	221347	885810	219000	885420	0.657	1.558	0.34004	71	12	3620.9	0.63	0	2.9	Pelton	171.6	150	2.9	0.8	0.55	35	1.479	0.4	0.0998	7.0134
Highland	Garbh Allt	237597	931485	238346	931965	0.684	1.2468	0.3326	68	11	2997.2	0.5	1.61	4.02	Pelton	170	163	0.96	0.8	0.52	25	1.092	0.23	0.0516	6.5974
Highland	Allt na Fea rna	232618	811989	232368	813431	0.655	1.2616	0.32603	69	11	3015.5	0.53	0.68	1.75	Pelton	175.9	165	1.75	0.8	0.49	25	0.946	0.25	0.0566	8.8
Highland	Allt Poll Doire	171105	751907	170194	750667	0.811	1.9522	0.32037	74	13	4363.1	0.61	0	1.89	Francis	79	71.7	1.69	1.3	1.39	40	5.076	1.08	0.2044	29.786
Highland	River Farrar	235232	841584	235626	840391	0.543	0.9242	0.31682	65	10	2337.3	0.49	0	2.35	Pelton	199.5	179	1.38	0.6	0.37	25	0.977	0.15	0.0294	7.7794
Argyll and Bute	Abhain a' Bhealaich	197204	705648	195785	707516	0.65	1.5574	0.31154	72	12	3572.8	0.63	0.28	2.81	Pelton	170	149	2.81	0.8	0.54	35	2.254	0.37	0.0931	12.524
Highland	Allt na Cloiche	181854	759657	181875	760269	0.38	0.6219	0.30479	59	8	1723.5	0.52	0	0.74	Pelton	146.7	138	0.74	0.6	0.34	25	0.701	0.16	0.0356	4.4645

Run-of-River Sites (15% Discount Rate)

County	River	Intake Easting	Intake Northing	Power house Easting	Power house Northing	Power (MW)	Total cost (M£)	NPV (M£)	LEC (£/MWh)	Discounted Payback Period	Energy production (MWh/year)	CF	Line distance (km)	Road distance (km)	Turbine type	Gross Head (m)	Net Head (m)	Penstock Length (km)	Penstock diameter (m)	Qd (m^3s^{-1})	Qd (FDC percentile)	Q10 (m^3s^{-1})	Q50 (m^3s^{-1})	Q90 (m^3s^{-1})	Catchmnet area (km^2)
Highland	Alltan Odhar	195111	847210	195401	845706	0.989	1.9757	0.26186	75	14	4312.9	0.5	0.77	2.3	Pelton	118.7	106	1.73	1.1	1.17	30	2.971	0.45	0.0614	12.562
Highland	Drundreggan Reservoir	234754	816313	235385	815772	0.435	0.7946	0.2587	66	10	1987.1	0.52	0	1	Pelton	127.9	118	1	0.7	0.46	25	0.986	0.22	0.0431	9.3095
Highland	Allt Toll a' Mhuic	223194	840373	222486	839140	0.69	1.122	0.2538	70	12	2622.2	0.43	0	1.63	Pelton	210.3	195	1.63	0.7	0.44	25	1.036	0.12	0.0187	4.4579
East Ayrshire	River Ayr	249372	623208	249161	623360	0.982	2.4316	0.25101	77	16	5190.8	0.6	1.7	0.48	Francis	25.9	25.3	0.28	2.5	5.02	40	12.81	4.06	0.6041	217.91
South Lanarkshire	River Clyde	281628	646508	282435	647049	0.57	1.5577	0.24645	74	13	3466.3	0.69	0.48	1.08	Francis	56.2	51.7	1.08	1.3	1.37	50	4.914	1.46	0.1969	86.772
Highland	Allt Chna imhean	203627	863552	202999	863305	0.361	0.6107	0.24169	63	9	1597.8	0.51	0.2	1.36	Pelton	190	177	0.79	0.5	0.25	25	0.567	0.11	0.0212	3.8881
Highland	Lochan na Cruaiche	172235	777068	171975	778415	0.523	0.9054	0.24161	68	11	2176.7	0.47	0.2	1.52	Pelton	218.3	202	1.52	0.6	0.32	25	0.686	0.11	0.0194	4.5313
Highland	Allt Garbh-choire	219121	837275	219481	838006	0.532	0.860	0.238	68	11	2080.7	0.45	0.0	1.0	Pelton	141.7	129	1.0	0.7	0.51	25	1.153	0.14	0.0201	7
Perth and Kinross	Allt an Fhionn	266667	725688	267022	724709	0.67	1.2549	0.23444	72	13	2851.6	0.49	1.97	1.19	Pelton	167.8	160	1.19	0.8	0.52	25	1.38	0.2	0.0312	12.441
Highland	Allt Baile nan Carn	227539	814681	227289	813182	0.529	1.0736	0.22706	71	12	2483.1	0.54	0.6	1.7	Pelton	169.6	155	1.7	0.7	0.42	25	0.824	0.22	0.0515	7.2717
Highland	Allt an Fhaing	184763	759771	184836	760603	0.387	0.6639	0.22648	65	10	1677.2	0.5	0.4	1.02	Pelton	214.4	199	1.02	0.5	0.24	25	0.516	0.1	0.0239	2.4455
Argyll and Bute	Abhainn Strathainn	185094	673366	186194	674116	0.529	0.9899	0.22013	71	12	2307.4	0.5	0.2	1.47	Pelton	157.9	143	1.47	0.7	0.46	25	1.017	0.19	0.0384	7.1518
Highland	Allt a' Choire Dhuibh	201955	836089	200276	836364	1.316	3.2136	0.21985	79	18	6676.1	0.58	4.4	5.06	Pelton	118.4	106	2.19	1.3	1.57	35	4.963	0.93	0.1735	34.947
Stirling	Allt Criche	232824	718151	232121	718584	2.47	3.4139	0.21471	80	18	7061.2	0.33	12.6	1.16	Pelton	275.1	264	0.96	1	1.18	15	1.604	0.14	0.0217	6.7753
Highland	Loch Ard a' Phuill	169868	773366	170055	772829	0.406	0.6219	0.21237	65	10	1571.4	0.44	0.2	0.64	Pelton	168.2	162	0.64	0.6	0.31	20	0.511	0.1	0.0185	2.8426
Highland	Loch Garraidh Mhair	217490	891020	216576	890603	0.337	0.6304	0.21045	65	10	1585	0.54	0.28	1.13	Pelton	209.2	196	1.13	0.5	0.21	25	0.408	0.11	0.0288	3.5632
Highland	Allt a' Choire Bhuidhe	257603	817918	256557	819404	0.686	1.5451	0.19989	76	14	3364.8	0.56	2.55	2.19	Pelton	222.3	204	2.19	0.7	0.42	25	0.764	0.24	0.0617	8.7147
Highland	River Taodail	195842	841724	194860	842264	0.311	0.8205	0.19714	70	11	1936.6	0.71	0	1.75	Pelton	91.5	84.4	1.35	0.8	0.46	50	2.966	0.5	0.0892	14.072
Argyll and Bute	Allt Dhoirrean	215556	732408	215646	730994	0.729	1.2186	0.19104	74	14	2708.8	0.42	0.2	1.65	Pelton	194.8	172	1.65	0.7	0.53	25	1.095	0.11	0.0012	2.0338
Highland	Allt a' Bhuiridh	177555	780726	177899	781746	0.729	1.2536	0.1898	74	14	2775.5	0.43	0.88	2.4	Pelton	160.6	149	1.23	0.8	0.61	25	1.283	0.15	0.0144	6.4286
Argyll and Bute	Leth Allt	205796	690273	204428	690268	0.638	1.2513	0.18357	75	14	2760.7	0.49	0	1.96	Pelton	145.3	128	1.76	0.8	0.62	30	1.946	0.21	0.0449	8.5836
Highland	Loch na h-Uidhe	194274	887470	194733	889912	3.764	8.1733	0.17939	82	22	16355	0.5	7.06	3.12	Francis	97	90.2	3.12	2.5	5.06	25	9.328	2.5	0.5134	78.873
Highland	Allt a' Choire Ghlais	226411	796583	227406	795995	1.536	2.4825	0.17725	79	17	5169.6	0.38	5	1.71	Pelton	214	203	1.51	1	0.95	20	1.702	0.18	0.0243	8.9852
Highland	River Coiltie	247163	827048	249493	827893	0.887	2.3844	0.17722	79	17	4976.6	0.64	1.33	3.07	Pelton	137.3	112	3.07	1	1	35	2.835	0.7	0.1349	33.892
Highland	Allt Eiteachan	260784	886524	262962	887725	0.667	1.7776	0.17692	77	16	3783.9	0.65	0	2.94	Pelton	141.2	122	2.94	0.9	0.68	35	1.559	0.52	0.1079	22.705
Argyll and Bute	Allt na Cuile Riabhaiche	206581	720441	206588	720979	0.333	0.5758	0.17074	67	10	1412.4	0.48	0.2	0.84	Pelton	152.3	147	0.64	0.6	0.28	25	0.696	0.11	0.0262	3.3013
Perth and Kinross	Falls of Keltney	276734	750477	277439	748993	0.524	1.3683	0.16876	76	15	2966.3	0.65	0.48	1.91	Pelton	104.2	97	1.91	1	0.68	40	3.333	0.51	0.0659	32.803
Highland	Abhainn Dubh	178599	853850	178609	854705	0.952	2.1572	0.1514	79	17	4487.9	0.54	4.19	2.2	Francis	90.6	83.4	1.1	1.2	1.4	30	3.227	0.81	0.1709	20.229
Highland	Allt Coire Giubhsachan	218320	769726	218650	768759	2.075	3.0423	0.14641	80	19	6218.7	0.34	6.97	9.64	Pelton	268.2	250	1.16	0.9	1.04	15	1.352	0.14	0.0042	4.1903
Highland	Loch Beag	263609	885751	264322	886530	0.339	0.7712	0.14501	72	13	1754	0.59	0	1.18	Pelton	103.4	97.9	1.18	0.8	0.43	30	0.899	0.27	0.0472	15.703
Highland	Lochan na Craoibhe	170676	786530	169852	785620	0.382	0.7842	0.13299	73	13	1759.8	0.53	0	2.12	Pelton	177	163	1.55	0.6	0.29	30	0.835	0.13	0.0261	4.3847
Highland	Allt Raon a' Chroisg	218362	889551	217229	889934	0.374	0.7192	0.12815	73	13	1624	0.5	0	1.66	Pelton	202.8	177	1.46	0.5	0.26	25	0.605	0.1	0.019	3.8279
Highland	Abhainn a' Choire	236743	926405	236498	925717	0.397	0.7483	0.12041	74	13	1668.4	0.48	1.13	0.79	Pelton	169.4	162	0.79	0.6	0.3	20	0.538	0.13	0.0319	3.0586
Argyll and Bute	Allt an t - Sidhein	217441	718833	215972	718213	0.745	1.3062	0.11821	78	16	2761.1	0.42	0	2.65	Pelton	207.5	183	1.97	0.7	0.51	25	1.116	0.11	0.0108	3.6699
Highland	Allt a' Choire Dhuibh Mhair	194706	859006	196057	857415	1.874	2.9213	0.11791	81	20	5934	0.36	8.6	2.94	Pelton	452.2	415	2.37	0.7	0.56	15	0.73	0.11	0.0082	2.1715
Argyll and Bute	Eas na Gea rr	199227	737178	198826	735490	1.15	2.0376	0.11459	80	18	4192.2	0.42	0.28	2.27	Pelton	167.6	150	2.27	1	0.96	25	2.131	0.18	0.0188	12.625
Highland	Loch a' Bhainne	227519	804209	227913	802994	0.361	0.7487	0.11388	74	14	1658.6	0.52	0.2	1.6	Pelton	170.2	159	1.4	0.6	0.28	25	0.565	0.14	0.0323	4.9378
Highland	Allt nan Carnan	188374	841630	189681	841118	0.396	0.8793	0.11319	76	15	1914	0.55	0	2.68	Pelton	160.2	137	1.71	0.6	0.36	30	0.935	0.18	0.0396	4.3316
Highland	Allt Leacachain	223703	876983	223253	876201	0.363	0.7046	0.10051	75	14	1549.9	0.49	0.28	0.98	Pelton	138.7	125	0.98	0.6	0.36	25	0.818	0.14	0.0278	4.7816
Argyll and Bute	Loch Airigh na Creige	201140	703711	202032	702700	0.327	0.7262	0.09773	75	14	1587.7	0.55	0.4	1.61	Pelton	209.3	191	1.61	0.5	0.21	30	0.69	0.11	0.0274	3.689

Run-of-River Sites (15% Discount Rate)

County	River	Intake Easting	Intake Northing	Power house Easting	Power house Northing	Power (MW)	Total cost (M£)	NPV (M£)	LEC (£/MWh)	Discounted Payback Period	Energy production (MWh/year)	CF	Line distance (km)	Road distance (km)	Turbine type	Gross Head (m)	Net Head (m)	Penstock Length (km)	Penstock diameter (m)	Qd (m^3s^{-1})	Qd (FDC percentile)	Q10 (m^3s^{-1})	Q50 (m^3s^{-1})	Q90 (m^3s^{-1})	Catchmnet area (km^2)
Stirling	Falls of Leny	259176	708718	259848	708813	1.322	3.4216	0.08009	82	22	6854.9	0.59	0.4	0.82	Francis	29.7	27	0.82	2.5	6.29	45	34.4	5.15	0.626	195.62
Argyll and Bute	Kilduskland Resr	184347	686777	184976	686580	0.195	0.457	0.07771	73	13	1025.8	0.6	0	0.77	Pelton	101.4	96.4	0.77	0.6	0.25	30	0.71	0.16	0.0349	3.5415
Highland	River Rha	140081	864831	139455	864162	0.287	0.7442	0.07717	77	16	1589.3	0.63	0.77	0.98	Pelton	90.1	80.8	0.98	0.7	0.44	35	1.083	0.33	0.0732	12.077
Argyll and Bute	Abhainn Doire Dhubhaig	149868	734202	149145	735838	0.491	1.0796	0.07446	79	17	2243.8	0.52	0.68	2.02	Pelton	199.7	174	2.02	0.6	0.35	30	0.865	0.15	0.0222	5.2384
Highland	Allt Coire Mhuilidh	235225	865170	235399	863965	0.299	0.7257	0.07038	77	16	1541.7	0.59	0.2	1.38	Pelton	130.4	115	1.38	0.6	0.32	30	0.731	0.2	0.0428	7.3001
Highland	Allt Loch Carn nan Conbhairean	236808	917672	237693	918042	0.483	1.173	0.06927	80	18	2418.8	0.57	2.08	1.07	Pelton	100.5	94.4	1.07	0.9	0.64	30	1.427	0.4	0.0955	7.1717
Argyll and Bute	Abhainn na h-Uamha	151775	735815	150792	736785	0.404	0.8006	0.06797	78	17	1685	0.48	0	1.55	Pelton	170	152	1.55	0.6	0.33	30	0.873	0.1	0.0124	4.5098
Argyll and Bute	Allt Dubh	185284	677586	185945	677186	0.353	0.6587	0.06441	77	16	1400.2	0.45	0.2	0.87	Pelton	137.7	127	0.87	0.6	0.34	25	0.77	0.1	0.0225	4.2907
Highland	Abhainn Righ	203210	762777	203049	762957	0.236	0.516	0.06246	76	15	1116.7	0.54	0	1.37	Pelton	60.9	59.2	0.27	0.8	0.49	40	2.89	0.24	0.0272	16.459
Highland	Loch na Maine Beag	220455	861290	221067	860557	0.219	0.5136	0.06233	76	15	1111.6	0.58	0	1.3	Pelton	142.4	130	1.1	0.5	0.21	30	0.47	0.13	0.0305	4.5825
Highland	Allt Creag an Eighich	176966	761449	176335	760813	0.35	0.7767	0.06031	79	17	1625.3	0.53	0.2	1.04	Pelton	99.3	93.7	1.04	0.8	0.46	35	1.557	0.21	0.0268	7.7516
North Ayrshire	Gogo Water	222836	659916	221236	659194	0.485	1.2551	0.05926	81	19	2563.7	0.6	0.4	2.65	Pelton	170.4	149	2.65	0.7	0.4	30	1.182	0.26	0.0556	10.018
Highland	Aldernaig Burn	229608	801723	229768	801039	0.212	0.5973	0.05922	77	16	1271.1	0.69	0	0.78	Pelton	58.9	54.3	0.78	0.8	0.48	45	1.886	0.47	0.0959	18.018
Highland	Abhainn an Fhasaigh	202079	866327	201137	865596	0.726	1.474	0.05714	81	20	2990.2	0.47	1.45	3.15	Pelton	130.2	120	1.3	0.9	0.76	25	1.604	0.27	0.0386	9.2704
Highland	Abhainn Ghardail	183511	754738	183416	753491	0.649	1.2827	0.05351	81	20	2608.4	0.46	0	1.97	Pelton	160	144	1.97	0.8	0.56	30	1.512	0.15	0.0125	5.6069
Highland	River Farrar	236466	840040	237181	839806	0.279	0.64	0.05245	78	17	1343.8	0.55	0.2	0.85	Pelton	89.1	81.6	0.85	0.7	0.42	30	1.323	0.22	0.0394	10.805
Highland	Allt Daingean	224130	804210	224449	803191	0.207	0.5273	0.04795	78	16	1114.9	0.61	0	1.43	Pelton	138.2	125	1.23	0.5	0.2	35	0.706	0.14	0.0293	5.0985
Highland	Allt Cailtidh	260107	820258	259557	822000	0.668	1.6339	0.04652	82	21	3287	0.56	2.18	2.24	Pelton	159.9	140	2.24	0.8	0.6	25	1.103	0.34	0.0916	12.333
Highland	Achriesgill Water	226761	952880	225606	952550	0.33	0.8692	0.04125	81	19	1775.8	0.61	0.48	1.41	Pelton	106.5	101	1.41	0.8	0.41	35	1.059	0.29	0.059	10.131
Highland	Allt Coire nam Bra than	233056	838983	233216	839457	0.229	0.5263	0.0373	79	17	1095.5	0.55	0.4	0.84	Pelton	91.9	85.4	0.56	0.6	0.33	30	0.966	0.17	0.0219	11.361
Highland	River Lael	222825	883729	221163	885040	0.698	1.5655	0.02455	83	23	3116.4	0.51	2.2	2.31	Pelton	216.1	193	2.31	0.7	0.45	30	1.191	0.19	0.0307	6.9932
Highland	Allt a' Mhadaidh	222560	874560	223663	875428	0.454	1.1551	0.02291	82	22	2307.3	0.58	0.57	2.01	Pelton	101.7	93.4	1.61	0.9	0.61	35	1.845	0.38	0.0761	9.4994
Highland	Allt Achaidh Luachraich	225683	804844	225563	803509	0.256	0.6893	0.021	82	21	1389	0.62	0.4	2	Pelton	177.6	159	1.8	0.5	0.2	35	0.615	0.14	0.0319	4.4811
Highland	River Attadale	194359	837182	194251	837809	0.141	0.3667	0.01919	80	19	752.14	0.61	0	0.74	Pelton	103.6	97.6	0.74	0.5	0.18	35	0.533	0.12	0.0224	4.5353
Highland	Allt Coire Mhuilidh	233259	864416	233139	863324	0.186	0.5009	0.01677	81	20	1011.8	0.62	0	1.22	Pelton	128.8	117	1.22	0.5	0.19	35	0.53	0.14	0.0303	5.553
Highland	Allt a' Bhealaich Mhair	242623	866716	241268	867326	0.264	0.625	0.015	82	22	1252	0.54	0.0	1.6	Pelton	170.3	151	1.6	0.5	0.21	30	0.611	0.1	0.0187	7
Highland	River Rha	140430	863605	139869	863781	0.199	0.6278	0.01404	82	22	1256.7	0.72	0.57	0.65	Pelton	51.8	49.5	0.65	0.9	0.5	50	2.163	0.57	0.1135	18.834

Impoundent Sites (5% Discount Rate)

County	River	Intake Easting	Intake Northing	Power house Easting	Power house Northing	Power (MW)	Dam height (m)	Dam width (m)	Impoundment volume (Mm^3)	Total cost (M£)	NPV (M£)	LEC (£/MWh)	Discounted Payback Period	Energy production (MWh/year)	CF	line distance (km)	road distance (km)	Turbine type	Gross Head (m)	Net Head (m)	Penstock Length (km)	Penstock diameter (m)	Qd (m^3s^{-1})	Q10 (m^3s^{-1})	Q50 (m^3s^{-1})	Q90 (m^3s^{-1})	Daily half hours operation	Catchmnet area (km^2)
Highland	Falls of Kirkaig	211275	917798	207972	919340	7.0	15	110	189.0	18	45	40	5	44947	0.73	1	5	Francis	113	103	4.2	3	7.5	14.4	4.3	1.0	36	136.7
Highland	Allt Coire Eaghainn	217489	768908	215348	768408	13.8	35	80	13.7	17	33	58	6	28958	0.24	3	3	Francis	169	154	2.9	2.9	9.8	7.7	1.2	0.07	12	31.7
Highland	Allt na h-Eilde	221459	762916	220092	761474	4.8	15	190	11.5	7	32	27	3	25767	0.61	0	5	Pelton	324	295	2.5	1.4	1.9	3.9	0.5	0.08	30	17.1
Highland	Allt Coire-lochain	202846	825159	200551	826603	4.6	15	340	8.2	11	22	48	6	22236	0.56	7	4	Pelton	307	279	3.6	1.5	1.9	3.7	0.6	0.08	28	15.1
Highland	River Talladale	191668	867032	191946	870034	4.3	5	370	4.2	8	19	44	5	18393	0.48	3	8	Francis	220	200	3.5	1.7	2.4	4.4	1.0	0.2	25	19.7
Highland	River Glass	258170	866425	260683	866572	3.1	15	230	2.3	9	14	49	7	16954	0.62	2	2	Francis	105	95	3.0	2.2	3.6	10.4	2.7	0.54	42	115.9
Highland	Allt Briste	226229	935195	224983	934037	6.0	5	80	11.0	8	12	68	7	11044	0.21	9	2	Francis	169	154	2.1	2	4.3	2.9	0.7	0.2	10	21.5
Highland	Abhainn Chia-aig	218137	790483	217597	788900	4.8	25	120	1.6	9	11	63	8	14425	0.34	13	2	Francis	195	178	1.9	1.7	3	4.3	0.5	0.07	26	19.4
Highland	Lochan nan Leacann Dearga	182573	867145	181371	869295	3.2	5	660	4.2	8	11	59	8	13353	0.48	4	8	Francis	154	140	3.2	1.8	2.5	4.4	1.1	0.3	26	21.0
Highland	Black Water or Uisge Dubh	200149	837782	200028	836657	3.7	20	140	2.3	7	11	55	7	12608	0.39	2	8	Francis	102	93	1.3	2.1	4.4	7.8	1.5	0.3	29	36.6
Highland	Allt a' Chonais	206842	848372	204623	849166	3.4	10	120	3.2	7	10	61	8	11794	0.39	0	3	Francis	200	182	2.8	1.6	2.1	2.9	0.4	0.0	22	12.5
Perth and Kinross	Allt a' Ghlas Choire	296067	780150	298290	779384	4.1	25	210	8.1	15	8	84	13	16767	0.46	18	14	Francis	143	130	2.9	2.1	3.5	5.7	1.1	0.30	24	54.4
Highland	An Garbh-allt	179070	850855	178549	854580	1.4	10	460	7.7	6	7	56	8	10237	0.84	4	6	Pelton	195	178	4.9	1.3	0.9	2.4	0.5	0.11	44	13.7
Highland	Loch Coire na Creiche	186763	762266	185282	760779	2.1	5	340	1.2	5	7	54	7	8168	0.45	1	5	Pelton	288	262	2.7	1.1	0.9	1.6	0.2	0.03	29	4.8
Highland	Allt Poll Doire	171318	752651	170194	750667	1.7	15	190	10.3	6	7	62	9	9681	0.65	0	3	Francis	104	95	2.6	1.8	2	4.6	1.0	0.18	32	27.3
Argyll and Bute	Eagle's Fall	222759	714105	221617	714787	2.1	10	170	0.5	3	7	46	6	6859	0.37	1	2	Pelton	380	346	1.6	0.9	0.7	1.2	0.1	0.04	28	5.0
Highland	Loch na h-Oidhche	188308	866955	187173	869320	1.2	5	440	3.2	4	6	50	7	8364	0.83	2	8	Pelton	206	187	3.9	1.1	0.7	1.9	0.4	0.1	43	8.8
Stirling	Allt DhÃ¹in Croisg	254219	738703	252852	736302	1.4	5	240	0.6	3	6	42	6	6851	0.57	0	3	Pelton	339	309	3.2	0.9	0.5	1.4	0.1	0.02	43	8.6
Angus	Falls of Damff	338303	778549	338825	780271	4.4	15	180	2.0	9	6	84	12	9996	0.26	19	2	Francis	267	243	2.1	1.4	2	2.0	0.4	0.06	18	26.3
Stirling	Dubh Eas	229657	720818	231740	720255	3.3	15	180	1.2	8	5	79	12	9689	0.34	13	3	Francis	200	182	2.5	1.5	2	3.3	0.4	0.10	25	20.6
Highland	Allt Coire Shaile	212800	842557	212686	841388	3.6	10	160	2.8	5	5	85	10	6314	0.20	8	12	Francis	193	176	1.4	1.5	2.3	1.6	0.2	0.03	10	6.0
Highland	Dubh Lighe	194405	781581	193320	780382	1.6	20	110	1.9	5	5	62	9	7422	0.53	1	5	Francis	98	89	1.9	1.7	2	4.2	0.5	0.02	38	13.8
Highland	Lochan Lice	248741	880115	250236	878476	2.2	5	160	0.3	6	5	72	11	8296	0.44	8	3	Francis	132	120	3.1	1.7	2	4.6	1.4	0.36	32	43.7
Highland	Allt a' Chaorainn	219816	750497	219556	751034	3.0	10	240	0.5	6	5	70	11	8663	0.33	9	6	Francis	105	96	0.7	1.7	3.5	5.9	0.6	0.0	36	21.9
Highland	Loch FÃ¨ith an Leathaid	217777	922776	215195	924398	1.1	10	120	6.6	4	4	62	9	6650	0.70	6	4	Pelton	193	175	3.5	1.1	0.7	1.5	0.4	0.1	36	12.6
Argyll and Bute	Allt Chaluim	224007	721527	224488	720509	3.1	15	260	0.9	7	4	83	12	8461	0.31	6	2	Francis	188	171	1.7	1.5	2	3.0	0.3	0.06	23	13.6
Highland	Loch BlÃ ir	205611	793687	205348	792392	1.2	5	110	3.4	4	4	66	9	5315	0.49	14	8	Pelton	260	236	1.5	0.9	0.6	1.1	0.2	0.04	24	5.3
Highland	Alltan Glas	195001	848445	195401	845706	1.2	5	260	0.6	4	4	56	9	6058	0.60	1	5	Pelton	161	146	3.1	1.2	0.9	2.4	0.3	0.0	47	10.5
Highland	Allt Garbh	217459	819693	218025	822122	1.1	5	190	1.8	4	3	67	11	6175	0.66	9	3	Pelton	191	174	3.3	1.1	0.7	1.9	0.2	0.04	39	8.2
Highland	Loch a' Bhainne	227519	804199	227878	803100	1.6	5	180	1.9	2	3	78	9	3038	0.22	0	1	Pelton	250	228	1.3	0.9	0.8	0.6	0.1	0.03	10	4.9
Highland	Abhainn na Glasa	244815	879166	245726	879823	2.0	5	280	2.7	5	3	93	13	5371	0.31	12	1	Francis	114	104	1.2	1.5	2.1	2.5	0.8	0.21	15	25.0
Argyll and Bute	Airigh nan Lochan	207653	747150	205759	747867	1.1	20	120	1.7	6	3	77	14	7310	0.74	10	5	Pelton	235	213	2.3	1	0.6	1.8	0.2	0.04	46	9.7
Highland	Allt an Tireidh	244121	932414	244513	930790	0.6	5	150	1.9	3	2	72	12	3640	0.65	6	6	Pelton	133	121	1.9	1	0.6	1.4	0.3	0.05	36	6.8
Perth and Kinross	Allt Mhairc	288840	776602	288392	772196	1.3	10	160	1.3	6	2	96	17	6079	0.55	11	7	Pelton	311	283	5.0	1	0.5	1.0	0.2	0.05	29	8.3
Argyll and Bute	Allt Eilidh	206766	753193	206648	751605	1.1	5	330	0.7	4	1	88	16	4553	0.49	11	2	Pelton	191	174	1.8	1	0.7	1.4	0.1	0.0	36	5.0
Dumfries and Galloway	Kello Water	269223	608951	271072	608841	0.6	15	70	0.3	3	1	77	14	3344	0.59	2	6	Pelton	133	121	2.1	1	0.6	2.1	0.3	0.07	46	15.3
Highland	Allt a' Chaorainn	269083	801224	269254	799512	0.6	5	180	0.1	2	1	90	16	2045	0.38	1	2	Pelton	152	138	1.9	0.9	0.5	1.1	0.2	0.05	31	11.0
Perth and Kinross	Allt Chaldar	246787	759864	246493	757137	0.5	5	140	3.2	2	1	95	18	2477	0.63	0	4	Pelton	112	102	3.9	1.1	0.5	1.0	0.2	0.04	31	13.0

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